GEOLOGY AND EXPLORATION GEOCHEMISTRY OF THE GLACIAL DEPOSITS OF NORTHEASTERN ITASCA COUNTY, MINNESOTA

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Late Wisconsinan glaciation produced two lobes of the Laurentide ice sheet in northeastern Minnesota: the Rainy Lobe and St. Louis Sublobe of the Des Moines Lobe. In Itasca County, deposits of the St. Louis Sublobe of the Des Moines Lobe have come in contact with, and have overridden deposits of the Rainy Lobe. The Rainy Lobe ice advanced from the northeast across the Precambrian Shield, depositing a brown sandy non-calcareous till. Deposits of the Rainy Lobe in the area are referred to as Nashwauk Drift. As the ice moved in a southwesterly direction over the crest of the Giants Range, it incorporated a large percentage of granite cobbles and boulders into its drift. Other rock fragments include metavolcanic and metasedimentary rocks of local origin, with minor basalt, gabbro and granophyre. The St. Louis Sublobe entered Minnesota from the northwest, overriding the deposits of the Rainy Lobe. St.Louis Sublobe drift, referred to as Caribou Drift, consists of a thick supraglacial accumulation of calcareous sand and gravel. The till facies is a silty, calcareous flow till containing abundant granitic and metamorphic clasts, with Paleozoic carbonate and Cretaceous shale.

Groundwater, lake water and lake sediment were sampled and analyzed for Co, Cu, Ni, Zn, Fe, Mn, Ca, Mg, K, and Na, to chemically characterize the surficial deposits. Specific conductivity , pH, and depth were also measured at each site. Multivariate statistical procedures were used to differentiate the samples, then characterize each group. Cluster analysis successfully separated the samples into two groups, which correspond to the two drift types. The dominant influence on the chemistry of the samples is the drift lithology, not climate, bedrock lithology or vegetation. Results of discriminant analysis and t-tests show that pH, Ca, Mg, Na, Fe, Mn, Cu and Zn, are the variables that best distinguish the drift types. Ca, Mg, Mn, and pH are enriched in the St. Louis Sublobe samples, with Fe, Cu, Zn, and Na enriched in Rainy Lobe samples. The composition of the drift is a result of processes operating in the surficial environment, e.g., oxidation-reduction, organic complexing, and bedrock interactions.

The chemical differences detected in the analysis suggest not only that both drift types are favorable for the migration of metal ions, but that the dominant influence on the chemistry of the two systems is the drift lithology. The inhibiting factor in the success of their use as geochemical sampling media is thought to involve their physical rather than chemical nature. Rainy Lobe deposits, thin occurrences of locally derived basal till appear to be chemicalaly and physically amenable to exploration geochemistry. The great thickness of the supraglacial sediments making up the Caribou Drift is thought to act as an effective barrier to circulating and oxidizing groundwaters.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

FIGURES

TABLES.

INTRODUCTION

During the past ten years, the Minerals Division of the Minnesota Department of Natural Resources has conducted various geologic surveys in an attempt to evaluate the mineral potential of state controlled lands. Of these investigations, reconnaissance geochemical exploration in glaciated terrain has been used, generally in conjunction with existing geologic and geophysical data, as a means of delineating the local bedrock, and more significantly as a means of delineating potential mineralization. It has been found (Dean and Gorham, 1976; Coker and others, 1979) that for certain physical and chemical parameters, hydrogeochemical and lithogeochemical samples will reflect the chemistry of the underlying bedrock. Previous geochemical investigations by the Minnesota Department of Natural Resources have been conducted in Cook, Lake, and St. Louis counties, where the Quaternary deposits consist of drift of the Rainy Lobe. These deposits are thin and sandy, and are thus amenable to exploration geochemistry. West of the Rainy Lobe drift, however, in an area blanketed by deposits of the St. Louis Sublobe of the Des Moines Lobe, reconnaissance geochemical techniques have proven less successful. No significant difference could be detected between the natural variability expected in a chemical system and an anomaly. This drift is characteristically thicker and more clayey, rendering the deposits less permeable to groundwater transport and consequently, to exploration geochemistry.

The purpose of this investigation is to compare and contrast the physical and chemical nature of the Rainy Lobe and St. Louis Sublobe drift types as a means of interpreting the results of a lake sediment geochemical survey in the drift of the St. Louis Sublobe. To accomplish this, the Quaternary deposits of the area were mapped, and a traverse across the glacial deposits was chosen for water and lake sediment sampling, to see if these media would be chemically representative of the drift from which they were sampled. Conductivity, pH, loss-on-ignition (L.O.I.) and ten elements were chosen to depict the chemistry of the two systems.

Multivariate statistics have been used to provide a method which will develop a mathematical framework for organizing and structuring the geochemical observations. Attempts were also made to determine the following statistical parameters as means of characterizing the geological media:

1) mean, median, maximum, minimun, and standard deviation

2) detection of geologically important differences among populations

3) detection and evaluation of associations among variables

4) detection and evaluation of systematic patterns of geographical variation in the variables

In turn, the mathematical framework can be expressed or interpreted in terms of a geologic model which approximates the actual situation. The model is not unique; any number of equally logical models can be developed, dependent on the observed geology in the area. Even more important is the inductive reasoning of the geologist who serves as interpreter of the statistical results.

Location

The field area is located in northeastern Itasca County, Minnesota, encompassing the Sherry Lake, O'Leary Lake, Horsehead Lake, Heartly Lake, Balsam Lake, Anderson Lake, Coon Lake and Clubhouse Lake 7-1/2 minute quadrangles (Fig. 1). Parts of several surrounding quadrangles were also studied.

Physiography

The area described in this report lies in the Superior Upland physiographic province of Fenneman (1938). The terrain consists of Precambrian rocks of the southern extension of the Canadian shield, overlain by varying thicknesses of Quaternary drift. Wright (1972) refers to the region as the Chisholm-Embarrass area, a wedge-shaped area of low moraines and outwash plains. It is bordered on the south by the Giants Range, and on the north by Glacial Lake Agassiz Plains.

The area has been further subdivided on the basis of geomorphic features (University of Minnesota Agricultural Experiment Station, 1971, Minnesota Soil Atlas-Hibbing Sheet) into: the Nashwauk-Warba Moraine, the Marcell Moraine Complex, and the Prairie River Sand Plain. The southeastern section, the Nashwauk-Warba Moraine, is described as gently rolling to steep moraine consisting of a brown colored clay-loam till. On the northwest is the Marcell Moraine Complex, a prominent moraine of steep complex topography. Brown colored calcareous clay loam till covers this area, intermixed with thick outwash sand and gravel. Between the two till units is the

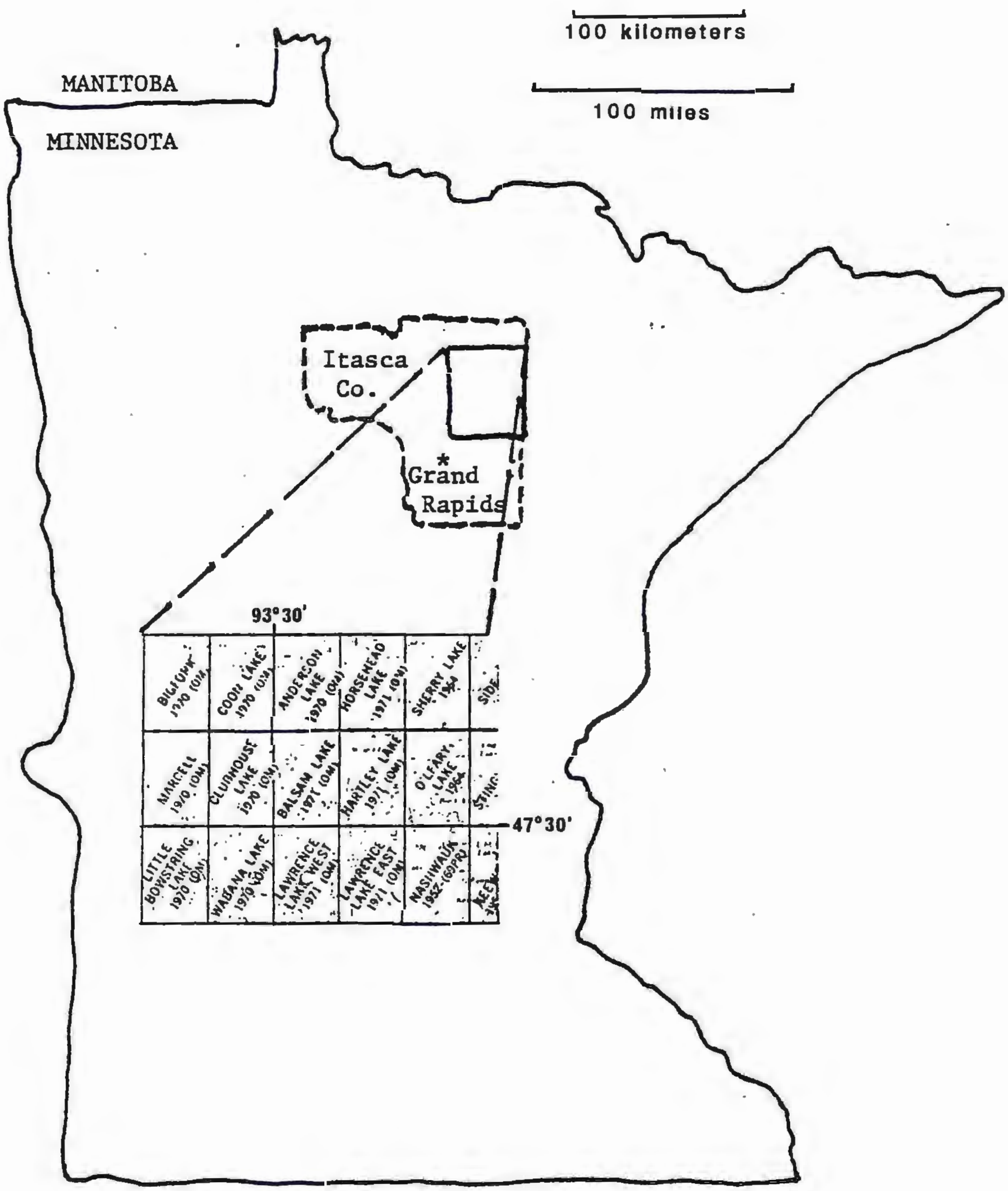


Figure 1. Location Map of the Report Area.

Prairie River Sand Plain, a gently rolling to nearly level topography consisting of thick fine- to medium-textured, water-laid sands. Lacustrine clays associated with Lake Agassiz have been traced along Bear River, and may occur along other tributaries as well. Many small and a few relatively large peat bogs occur throughout the Prairie River Sand Plains region.

The Laurentian Divide bisects the region, separating water flowing north to the Hudson Bay, from water flowing south via the Mississippi River to the Gulf of Mexico. The largest portion of the field area occurs within the Mississippi River Headwaters Watershed (Oakes and others, 1968). The Bigfork and Little Fork River Watersheds lie to the north of the Laurentian Divide; both are tributaries of the Rainy River (Lindholm and others, 1976; Helgesen and others, 1976). The drainage-basin divides correspond roughly to the drift boundaries, very effective for the purposes of this investigation in that waters drain opposite drift types.

Previous Investigations

Most previous work on the geology of the study area has concerned the bedrock geology. Because of the economic significance of the Mesabi-Vermilion Iron Range area, the bedrock geology has been extensively studied; an overview and bibliography can be found in Sims and Morey (1972). The bedrock geology of the area has been mapped by Sims and others, (1970), a portion of which is reproduced in this report.

Pioneer studies of the glacial geology were first undertaken by N. H. Winchell, the first state geologist, and his colleagues Warren Upham, J.E. Todd, and U.S. Grant. Together they differentiated two principal drift types in Minnesota; one derived from the northeast and one from the northwest. Winchell (1901) later investigated and published a map outlining the glacial lakes of Minnesota. Another pioneer was Frank Leverett, who in 1932 prepared and interpreted a more detailed map of the glacial geology of the state, based principally on morphologic features.

More recently, Wright and Ruhe (1965); Wright and Watts (1969); and Wright (1972a, 1972b) have reinterpreted much of Leverett's work, and based on the lithologic and stratigraphic relationships of the drift, have published several papers pertaining to the glacial history of Minnesota.

A series of publications on the glacial drift of the Mesabi-Vermilion Range has been prepared by Winter (1971, 1973a, 1973b) and Cotter and others (1964, 1965). These publications deal with the glacial geology as it relates to the ground water resources of the area, particularily important in the processing of iron ore onthe Range.

Two investigations of local interest are by Norvitch (1962), whose work concerns the Vermilion Moraine and surrounding geology, and Goltz (1969), concerning the surficial geology of the Chippewa National Forest.

Most recently Hobbs and others (1982) have compiled and reinterpreted the most recent stratigraphic and morphologic geologic information, which has culminated in a Quaternary geologic map of the state.

PART I: GEOLOGY
REGIONAL GEOLOGY

Bedrock Geology

The bedrock geology of Minnesota has played a major role in directing the flow of glacier ice. Minnesota consists of a series of topographic depressions and barriers that channeled and diverted advancing glacier ice. The direction and configurations of the ice were controlled directly by the bedrock topography, and indirectly by the relative resistance of the rocks involved. A variety of bedrock lithologies contributed to the glacial sediment of Minnesota, their provenance ultimately helping to delineate the flow patterns and sequence of the Wisconsinan Glaciation.

Early Precambrian rocks (Fig 2) form much of the bedrock surface of northern Minnesota. These rocks, typical of Archean greenstone-granite complexes, represent the southern extension of the Precambrian Shield, and can be subdivided into two major groups. The first group consists of volcanic and sedimentary rock types which have been metamorphosed to the greenschist facies; they are commonly referred to as greenstones. These rocks represent a westward extension of the Vermilion District of Minnesota, dated at approximately 2.7 billion years. Granitic and granodioritic rocks, mostly unmetamorphosed, form the other major rock type of the Precambrian Shield. The plutons include the Giants Range Granite and the Vermilion Batholith.

Diabase dikes of Middle Precambrian age (about 2.0 billion years) are present in many places in the Lower Precambrian rocks north of the Mesabi Range. They occupy at least three sets of fractures that were formed in early Precambrian time as part of the regional fracture pattern (Sims and others, 1972). Most occur in a northwestward trending belt, about 35 km wide, that extends from the western part of the Mesabi Range to Ontario, Canada.

Along the north shore of Lake Superior confined to a narrow belt that extends from Lake Superior through eastern Minnesota (Fig. 2) is a sequence of Late Precambrian mafic intrusive and extrusive igneous rocks. The sequence is Keweenawan in age, ranging from 1,200 to 900 million years old. The mafic extrusive rocks, assigned to the North Shore Volcanic Group, consist mainly of basaltic flows but include substantial volumes of intermediate and felsic rocks. Clastic material occurs locally both at the base and intercalated with the flows. The North Shore Volcanic Group is intruded by several cogenetic intrusive bodies, the largest of which is the Duluth Complex. The Duluth Complex is comprised of a sequence of southward-dipping sheet-like intrusions that are gabbroic in composition. The Complex extends from Duluth, Minnesota in an arcuate pattern 45 km north-easterly to the extreme tip of northeastern Minnesota. Felsic and intermediate rocks, including granophyric granite, are associated with the Duluth Complex, occurring discontinuously along its eastern margin.

Middle Precambrian rocks cover much of northeastern Minnesota, exposed to the west and northwest of the Mesabi Range. These rocks are assigned to the Animikie Group and comprise a northeastward-

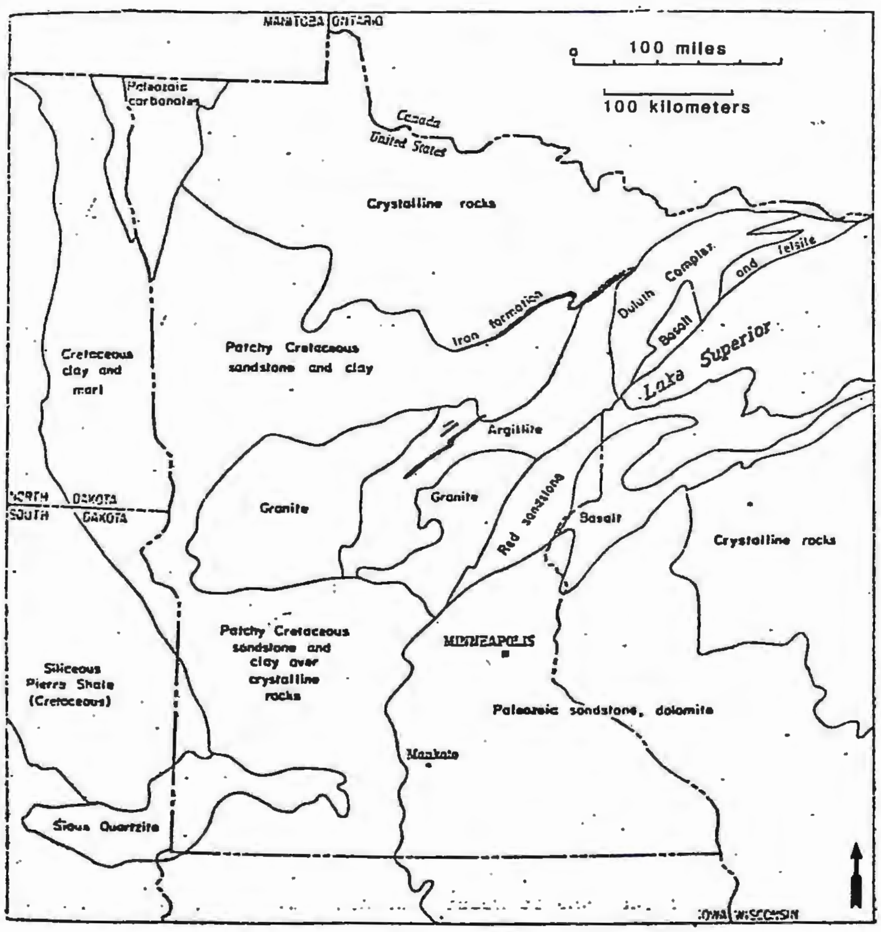


Figure 2. Generalized bedrock geology of Minnesota and parts of adjoining states (from, Wright, 1972, p. 519).

trending sediment wedge ranging from 50 to 500 meters in thickness. They range in age from 2.6 to 1.8 billion years. The Middle Precambrian stratigraphy of the Mesabi Range consists of the Pokagama Quartzite, the Biwabik Iron-Formation, and the argillite-siltstone-graywacke succession of the Virginia Formation.

The extreme northwestern portion of Minnesota consists of a series of non-resistant lithologies, primarily Ordovician limestone, dolomite, shale, and sandstone. These rocks underlie an eastward extension of the Great Plains, occurring along the edge of the Williston Basin. Cretaceous sediments, mostly friable greenish-gray sandstones and clays overlie much of the bedrock of western Minnesota, extending eastward into northern and southern Minnesota, but are thin and discontinuous. They are best known from exposures in the open pit mines of the Mesabi Range.

Pleistocene Geology

Four major lobes of the Laurentide Ice Sheet have been recognized in the Pleistocene glaciation of northern Minnesota. Most of the deposits have been attributed to the most recent stage of glaciation, the Wisconsinan, which began approximately 70,000 years ago (Wright, 1972). Older drifts are exposed in the deep open pits of the Mesabi-Vermilion Range (Winter, 1973a), although they cannot be traced continuously or correlated with older drifts elsewhere in the state.

Complex lithologies, stratigraphy and geomorphology are displayed by the Wisconsinan glacial sediments in northern Minnesota, reflecting the complex configuration of the lobes protruding from different areas over different geologic terrain. Wright (1972) has delineated several major phases of the Wisconsinan Stage in Minnesota (Fig 3). Differences in resistance to erosion of the many rock types of Minnesota was an important factor in determining the direction of ice movement across Minnesota. Several distinct lowlands in the bedrock surface, as shown in Figure 4, apparently channeled and diverted the flow of glacier ice.

The oldest surficial deposits in the field area were derived from the Rainy Lobe in the St. Croix Phase of glaciation. The Rainy Lobe began its advance into Minnesota approximately 20,000 years ago from the James Bay lowland of Canada. The Rainy Lobe moved into northern Minnesota, confined on its west by the Wadena Lobe, moving eastward from the Red Lakes Lowland, and contiguous on its east with the Superior Lobe, which occupied the Lake Superior basin. As the Rainy Lobe approached north-central Minnesota, its flow was interrupted by a topographic barrier- the Giants Range. The Giants Range presumably had a significant effect on the ability of the ice to carry its load (Winter, 1973). North of the Range, the ice was actively eroding, as indicated by the scoured, striated bedrock surfaces. South of the Range the Rainy Lobe was actively depositing drift, as indicated by the existence of a bouldery till.

Two groups of drumlins were formed by the advance of the Rainy Lobe in northeastern Minnesota, the Toimi drumlins of St. Louis and Lake Counties (Wright, 1956) and a smaller unnamed group to the north

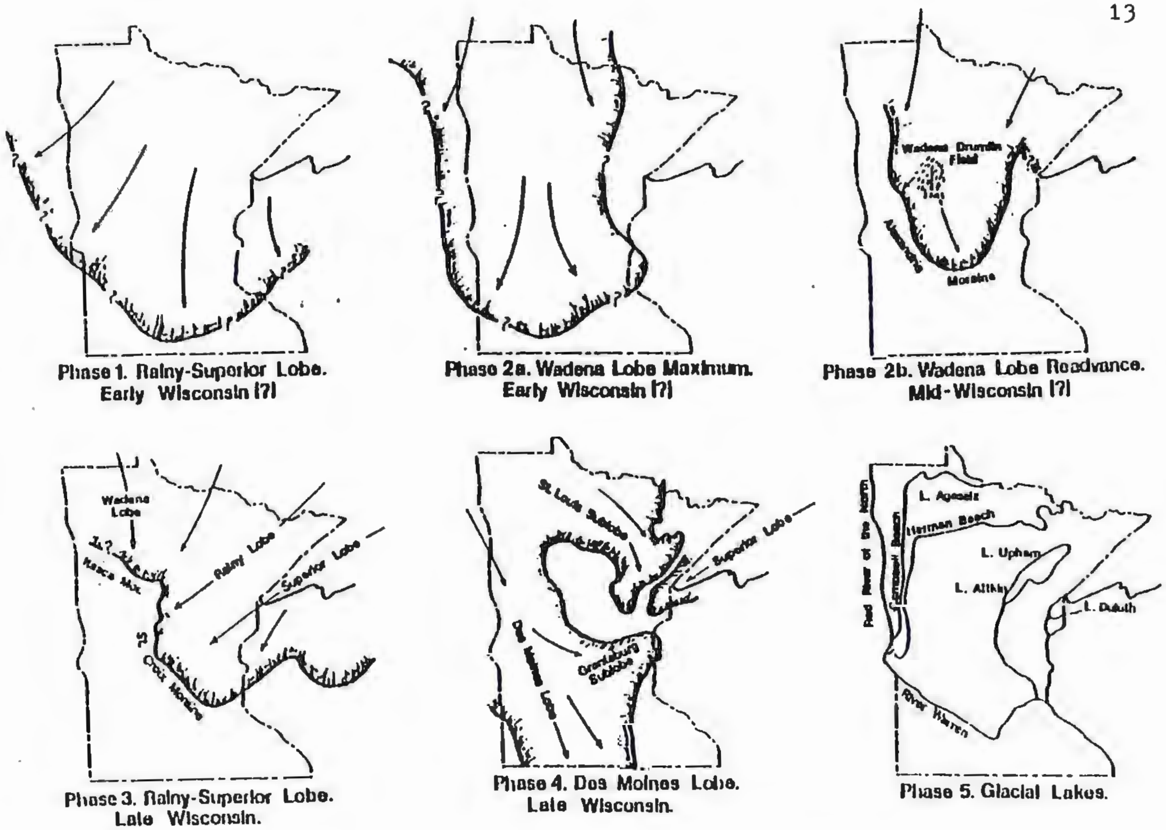


Figure 3. Major Phases of Wisconsinan Glaciation. From Wright, 1972.

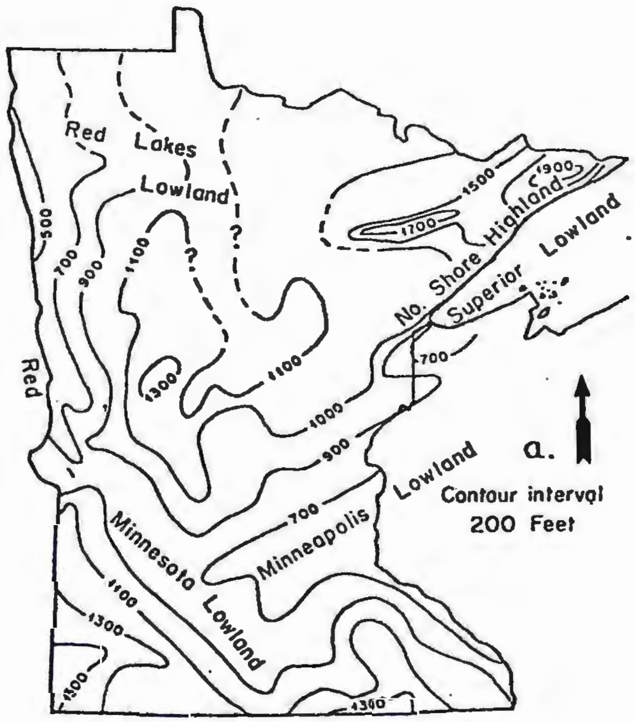


Figure 4. Bedrock Topography of Minnesota
from Wright, 1972

of Pengilly, also in St. Louis County (Cotter and others 1964). The Toimi Drumlins consist of gray, sandy, stony till with very little clay (Wright, 1972). The most conspicuous rock type is gabbro, which forms the bedrock in the area. Basal sediments from inter-drumlin depressions have been radiocarbon age-dated at 14,690 +390 radiocarbon years before present (RCYBP) (W-1763, Wright and others, 1969), and 15,850 +240 (I-5048 Wright, 1972).

The Rainy and Superior Lobes (the Patrician ice of Leverett, 1932) moved to the southwest from central Minnesota, beyond the confines of the Lake Superior basin. The Superior Lobe was a thicker, more rapidly moving ice stream, constricted by the deep Superior basin. At their confluence, the Superior Lobe "carried with it" on its western flank, the eastern flank of the Rainy Lobe (Wright and Ruhe, 1965). Together they formed the Pierz Drumlin Field. Basal sediments from the Pierz Drumlins have been dated at 20,500 RCYBP (I-5443, Wright and Ruhe, 1965), the maximum date for the ice advance of the St. Croix Phase.

The Laurentian ice terminated in central Minnesota, its margin marked by the St. Croix Moraine, extending from Walker, Minnesota, at an interlobate junction with the Itasca Moraine, southward, forming a broad 550 km long loop from the northwest to the northeast, through Wisconsin. The St. Croix Moraine is one of the most impressive topographic features in the Great Lakes region.

The Rainy Lobe retreated from the St. Croix Moraine at least 350 km to the north, probably into Canada (Wright, 1972). Wright and Watts (1969) suggest a minimum date of retreat of the ice between

14,000 and 16,000 years ago. During the Rainy lobe's retreat, much of the present day topography was formed. Several recessional moraines occur to the north of the Giants Range in the eastern Mesabi Range area. A large ice-crevasse filling near Calumet (Winter, 1971) was probably formed at the time. Many large blocks of stagnant Rainy Lobe ice survived the interstadial, indicating that the climate was at least cold enough to inhibit the thawing of ground ice (Wright, 1972).

During the retreat of the Rainy Lobe in the study area, meltwater was ponded between the receding ice front and the topographic high of the Giants Range. A small proglacial lake, Glacial Lake Norwood was formed (Winchell, 1901; Leverett, 1932; Winter, 1971). The lake eventually drained by way of the Embarrass Channel, a large trench that transects the Giants Range north of the city of Aurora, Minnesota. The Embarrass Channel presently contains evidence of a terrace at an elevation of 427 meters (1400 feet).

The second episode of glacial activity in northern Minnesota is represented by the deposits of the St. Louis Sublobe of the Des Moines Lobe. The main flow of the Des Moines Lobe originated in the Red River Valley of southern Manitoba, flowing southeastward along the Minnesota River Valley. Eight radiocarbon dates from coniferous wood at the base of the till in northern Iowa range from 13,680 to 14,470 RCYBC (Kemmis and others, 1981). The age of the advance is generally averaged at 14,000 years.

The St. Louis Sublobe, a late phase of the Des Moines Lobe, moved east-southeastward into central Minnesota, occupying the Red Lakes

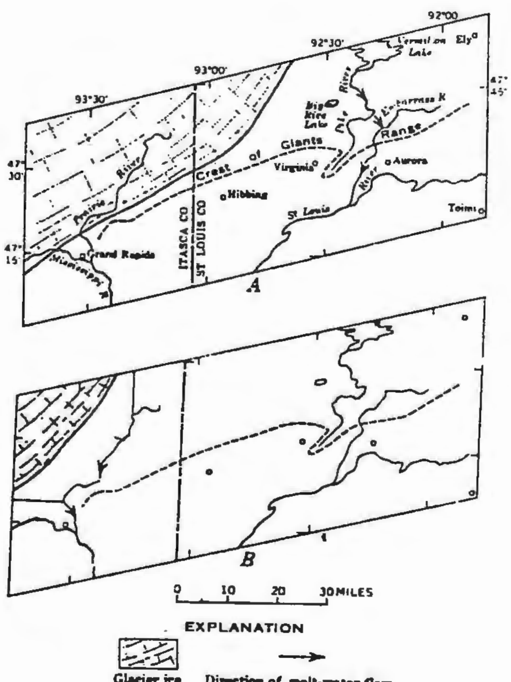
Lowland. This lowland had previously been occupied by the Wadena Lobe. As the St. Louis Sublobe approached north-central Minnesota, the topographic high of the Giants Range caused the Sublobe to split, part moving to the north, and part to the south. South of the Range the sub-Sublobe was again divided, by a topographic high in the Goodland area. The northern portion of this split moved to the northeast, along the southern flank of the Giants Range. The southern portion moved to the southeast, overriding and incorporating red lake clays into its drift. This is the Alborn Till of Baker (1964).

Diversions of the ice of the St. Louis Sublobe have resulted in variable, yet distinctive drift charateristics. North of the Itasca Moraine where the ice overrode Wadena Lobe drift, deposits are silty, and contain pebbles of shale (Wright, 1972). South of the range the till is typically a pebbly clay, its color buff to light red, dependent on the degree of incorporation of lake clays (Baker, 1964).

As the St. Louis Sublobe retreated from the area, meltwaters ponded between the ice front and higher topography to the east and south. A large shallow lake inundated the region, blanketing much of the area with a medium-grained, well-sorted sand. Leverett (1932) makes reference to beach deposits encircling a prominent ridge south of Nett Lake in southern Koochiching County. These deposits occur just over 427 meters (1400 feet), well above any known Lake Agassiz shoreline. Winter (1971), Goltz (1969) and Norvitch (1962) also cite evidence for the existence of a glacial lake occurring just over an altitude of 427 meters.

The lake reportedly drained first down the Pike River Valley, across a divide near Embarrass into the Embarrass channel, and into the St. Louis River (Fig. 5a). As ice to the south retreated enough to open a lower outlet, waters drained by way of the Prairie River to the Mississippi (Fig. 5b), Winter (1971).

Finally, as ice of the St. Louis Sublobe retreated further north, Glacial Lake Agassiz proper developed. Glacial Lake Agassiz attained a maximum elevation of 414 meters (1360 feet), reaching as far east as Koochiching County, to the northeast of the report area.



(After Winter, 1971)

Figure 5. Sequence of drainage of an unnamed glacial lake following retreat of the St. Louis sublobe from the north-central part of the area of report.

A. Upon retreat of the lobe north of the Giants Range, ponded lake waters west of Vermilion Lake and north of Big Rice Lake drained by way of the Pike and Embarrass Rivers to the St. Louis River.

B. Further retreat of the ice to northwest of the Prairie River opened the Prairie River as an outlet, and the higher eastern outlet was then abandoned.

SURFICIAL GEOLOGY OF THE REPORT AREA

Introduction

Two till units have been identified in the study area on the basis of matrix texture, matrix carbonate content, pebble lithology, and stratigraphic position. They are deposits of the Rainy Lobe, and St. Louis Sublobe, respectively. The eastern half of the report area consists of glacial sediments interpreted by the author to be derived from the Rainy Lobe in the St. Croix Phase of glaciation. The material is predominantly a brown, sandy, non-calcareous till, which, unlike typical Rainy Lobe till, is matrix dominated. Clast lithologies consist mainly of granite and metamorphic rocks of local origin, and also gabbro, basalt, and granophyre. These rock types are indicative of a northeastern source. Deposits of the Rainy Lobe in the report area, and in and around the city of Nashwauk have been informally referred to as "Nashwauk Drift" and are here (informally) defined as such. This drift can be stratigraphically correlated with the Sullivan Lake Formation of Gross (1982).

In the past, Nashwauk Drift was mapped and interpreted to be deposited by both the St. Louis Sublobe and the Rainy Lobe. Because of its matrix-dominated texture, most investigators have associated it with deposits of the St. Louis Sublobe, (Leverett, 1932; Wright, 1972; Wright and Ruhe, 1965; Wright and Watts, 1969; Cotter and others, 1964,1965). Winter (1971), working out the stratigraphic relationships of the glacial deposits of the Mesabi-Vermilion Range area mapped what the author has interpreted to be Rainy Lobe till as St. Louis Sublobe in origin, questioning its pebble orientation and radiocarbon age. He suggested that the "till" might be glacial lake sediments. Winter (1973), in an investigation of the "St. Louis Sublobe till" north of the Giants Range, found that "none of the samples contain pebbles indicating a northwest source" (p. C-36). He interpreted the sediments to be "probably" St. Louis Sublobe in origin, but admitted uncertainty in the conclusion. Goebel (1979) mapped the deposits north of the Giants Range as Rainy Lobe in origin. Hobbs and others (1982), after field investigation with the author, also agreed to a Rainy Lobe origin, and mapped them as such.

The western portion of the field area is dominated by deposits of the St. Louis Sublobe of the Des Moines Lobe. The St. Louis Sublobe came in contact with, and in places overrode deposits of the Rainy Lobe. Deposits of the St. Louis Sublobe in the area represent the terminal moraine of the St. Louis Sublobe ice and consist of a thick supraglacial sequence. The till facies is a buff-colored, silty, calcareous till containing Paleozoic carbonates and Cretaceous shale, indicating a northwestern source. The "Caribou Drift" is here introduced as the informal lithostratigraphic name applied to St. Louis Sublobe Drift in the area. The till facies of the Caribou Drift can be correlated with the Alborn Till of Baker (1964).

Methods of Investigation

Field Methods

Field work began in the summer of 1981, and was completed during the summer of 1982. The geology was mapped directly on United States Geological Survey (USGS) topographic quadrangle maps (1:24000 series). The Hibbing Sheet Soil Atlas (scale 1:250,000) and high altitude aerial photographs (scale 1:90,000) were examined as aids to mapping. Investigations were made to determine what materials were present, their distribution, their physical properties, and how the different materials are stratigraphically related. Field observations included Munsell soil color, texture, pebble lithology, pebble fabric, and weathering characteristics.

Clast lithologies where determined from pebbles sieved through a U.S. Standard mesh screen with 13.33mm (1/2 inch) openings. Cobble sized clasts (greater than 64mm) were discarded. Fabric analyses were made at several locations throughout the report area, on elongate stones with a length:width ratio of at least 1.5:1. Paleocurrent directions were measured at three locations.

Surficial deposits were examined from shallow roadcuts, in gravel pits, with a hand auger, and with the aid of a truck-mounted Giddings Soil Auger. Nine sites along the geochemical sampling traverse were chosen for drilling (Fig. 6). The rig drilled a 12-cm diameter hole, using 1 meter auger lengths. Drilling reached a maximum depth of 15 meters. The auger retained, except for surface contamination, a relatively undisturbed vertical section of the underlying sediment.

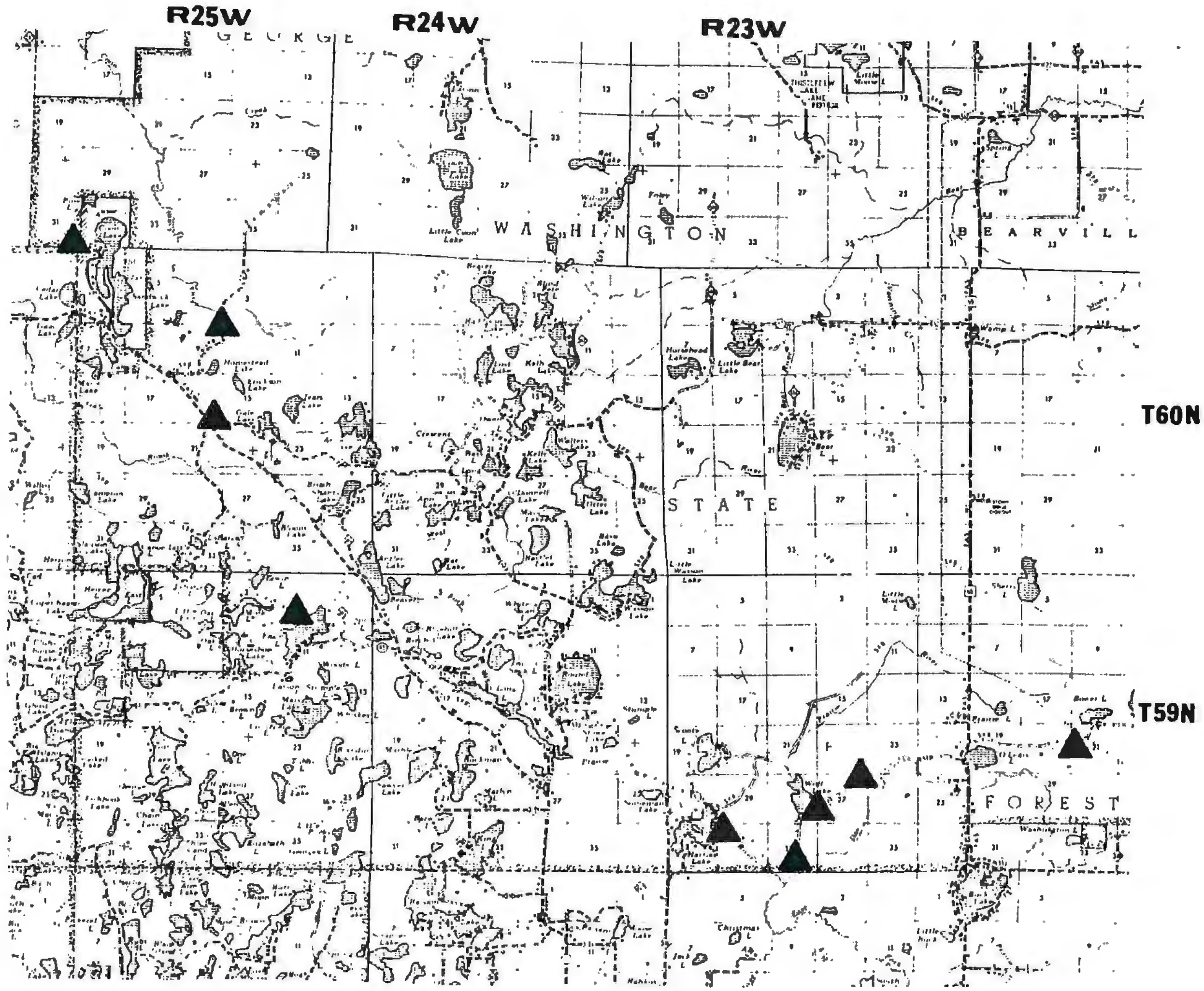


Figure 6. Drilling Location Map

The sediment recovered from the auger was described in the field, and samples were collected for laboratory analysis.

Additional stratigraphic information was obtained from well log data at the Minnesota Geological Survey, and from exploration drilling logs on file at the Minerals Division of the Minnesota Department of Natural Resources, Hibbing Minnesota.

Laboratory Methods

Laboratory analyses were conducted to determine the grain size distribution of the materials collected in the field. Grain size analyses were done on 64 samples, by sieving and by pipette following standard procedures outlined in Folk (1974), with modifications by Hallberg (1978). Till samples were analyzed for percent sand, silt, and clay, at one phi intervals. Grain size histograms, cumulative frequencies, and sorting statistics (mean, standard deviation, skewness, and kurtosis) were calculated and plotted by computer. The Wentworth Grade Scale boundaries (Table 1) were used in this study, with statistical calculations from Folk (1974).

TABLE 1. GRAIN SIZE PARAMETERS AND SORTING EQUATIONS

I. CLAST SIZE BOUNDARIES, DIAMETERS

	phi units	millimeters
Boulder	less than -8	greater than 256
Cobble	-6 to -8<	64 to 256<
Pebble	-2 to -6<	4 to 64<
Granule	-1 to -2<	2 to 4<
Sand	+4 to -1<	.063 to 2<
Silt	+8 to +4<	.004 to .063<
Clay	greater than +8	less than .004

II. SORTING EQUATIONS (After Folk, 1974)

Graphic Mean: $$Mz = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

Inclusive Graphic Standard Deviation: $$_{I} = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

Inclusive Graphic Skewness: $$SK_I = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

Graphic Kurtosis: $$K_G = \frac{\phi 95 - \phi 5}{2.44(\phi 75 - \phi 25)}$$

All statistics are calculated from points on a standard cumulative frequency curve. "Ø" refers to the grain size in phi units at a given percentile value (i.e. Ø16 corresponds to the grain size at which 16 percent of a given sample, by weight, is coarser-grained).

NASHWAUK DRIFT

General Characteristics

The Nashwauk Drift is the oldest unit exposed in the area. The Nashwauk Drift is comprised of two facies, till and outwash. The outwash facies consists of thin local occurrences of sand and gravel beneath the till facies. The outwash facies dominates the east-central portion of the field area (Fig. 7). The sediment consists of stratified coarse sand and gravel in the east, fining texturally westward.

The till facies consists of a thin, laterally discontinuous unit deposited subglacially by the southwesterly advancing Rainy Lobe in the St. Croix Phase of Wisconsinan Glaciation. The till is thin and patchy, draping either outwash sands and gravels or lows in the bedrock topography. Bedrock outcrops are common, occurring along the length of highway 65 (Fig. 7). Glacial striations were found in several locations on the exposed bedrock surface, their orientations presented on Figure 8.

The matrix of the till facies is brown in color, ranging from a grayish yellow-brown (10YR5/2) to a dull yellow-brown (10YR4/3) moist Munsell soil color. It is non-calcareous throughout. Texturally, the matrix is a muddy sand, with a mean sand:silt:clay ratio of 60:23:12. Results of the particle size analyses are presented in Figure 9.

Unlike typical Rainy Lobe till, the till facies of the Nashwauk Drift is matrix dominated; that is, sparsely pebbly. Large subangular boulders of local origin with a maximum diameter of 2 meters are commonly strewn on the surface. Glacial quarrying and deposition from

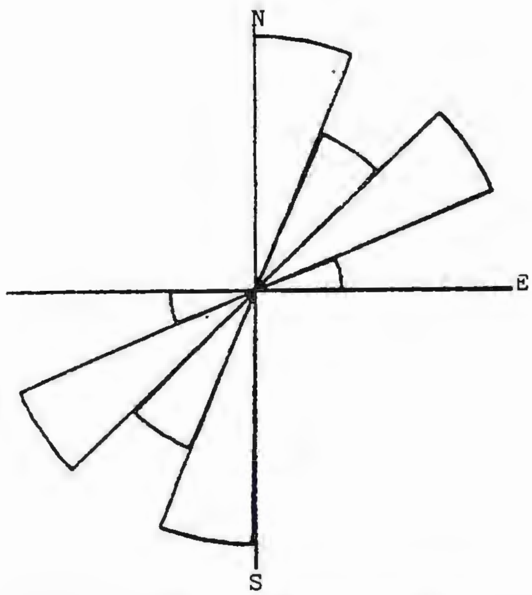


Figure 8. Glacial Striation Orientations
Total number: 9
Maximum per group: 3

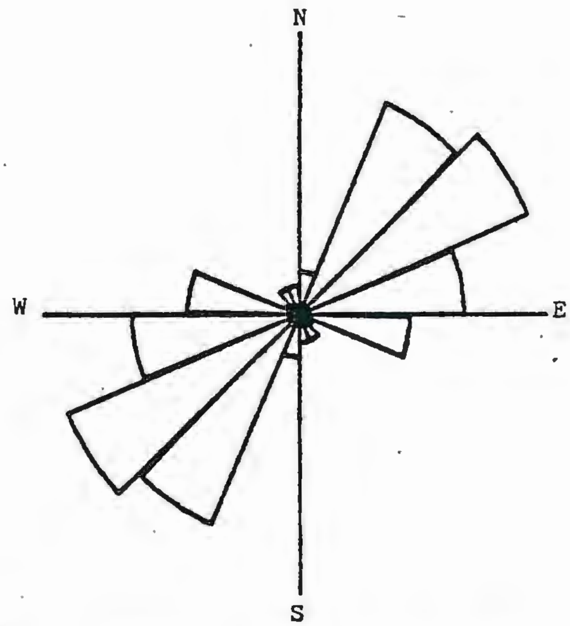


Figure 9. Nashwauk Drift Fabric
Total number: 62
Maximum per group: 18

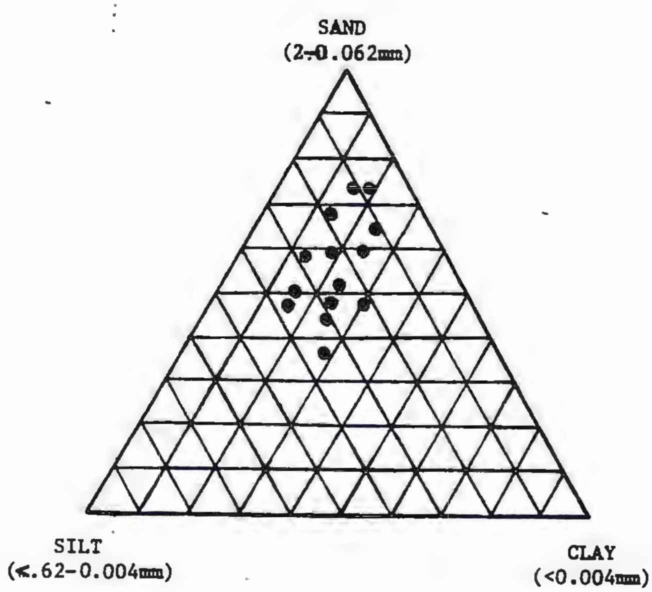


Figure10. Grain size distribution of Nashwauk Drift in the report area.

an englacial position are thought to be responsible for their existence. Stones from the till are predominantly granitic and metamorphic rocks with gabbro, basalt, and granophyre common. Two less abundant yet distinctive rock types are present: "redrock", an orthoclase-rich differentiate of the Duluth Complex, and the distinctive Lake Superior agate. Both are clearly indicative of a northeastern source.

Till fabric studies in the form of composite orientation measurements of elongate pebbles are presented in Figure 10. The fabric has a strong unimodal northeast-southwest pattern, which closely corresponds to the orientations of the striations on the bedrock surfaces.

Site-Specific Characteristics

The type locality for the till facies of the Nashwauk Drift is a 3.5 meter section of till exposed as a steep bank, and partly as the foundation for a building under construction on the south side of Co. Rd.539, of Section 28, T.58 N.and R.23 W. (28-58-23). The exposure consists of a dull yellowish brown (10YR4/3) thick sequence of till. The sediment, non-calcareous throughout its exposure, is matrix dominated, with a mean sand:silt:clay ratio of 49:28:23. Sparse lithic fragments range in size from 3 cm to 2 meters. They are composed of dominantly of granite and greenstone, with minor and granophyre. Fabric analysis of the long axes of the pebbles yield a northeast-southwest trend, consistent with those of the glacial striations on nearby bedrock.

In an Itasca County gravel pit near Buck Lake (21-59-22), a one-meter-thick cap of till overlies a thick section of stratified outwash. The contact between the outwash and the overlying till is sharp. The outwash sequence consists of very fine-grained planar and cross-bedded sand, directly overlying coarse sand and gravel. The coarse sediment exhibits trough cross-bedding, each set averaging about one meter thick. Surface boulders average 0.5 meter in diameter, with lithologies similar to those found at the type locality. Paleocurrent cross-bedding indicates flow toward the south and southwest.

The underlying sediment is a well-sorted, fine-grained sand, non-calcareous and oxidized to a dull yellow-orange (10YR6/2). Drilling at this location encountered still finer-grained sediment; non-calcareous throughout. A maximum depth of 5 meters was reached. The bottom of the section is in a non-calcareous brownish-gray (10YR4/1) silt.

The northern face of the Buck Lake pit (as of 9-1982) contains an ice-wedge cast, developed in the outwash sediment, and filled with the overlying Nashwauk till. Ice-wedges begin as tension cracks caused by differential frost heaving, and their existence is indicative of permafrost conditions (Pewe, 1973).

The coarse sequence grades westward, to the vicinity of Wolf Lake, into finer-grained, planer-bedded sands. A 2.5 meter section of outwash is exposed at the Highway 53 sandpit (26-59-23). The sands are well sorted, and the bedding is parallel and somewhat indistinct. The section consists of medium-grained sand (no pebbles) in a coarsening downward sequence. The sediment is oxidized to a dull yellow-brown color (10YR5/3), with rings and zones of more highly oxidized material common, probably organic in origin. The sediment is non-calcareous throughout.

Drilling below the surface of the sandpit encountered a sequence coarsening to a depth of 2 meters. The sediment consisted of a medium grained, subrounded, non-calcareous sand, again oxidized to a dull yellow-brown color. Beyond 2 meters, the sequence fined; bottoming in a gray silty clay, reduced to a N5/0. Colors in this zone were mixed as weak mottles and diffuse bands, grading into a more uniform material.

Depositional Environment

The Nashwauk till is characterized by: 1) a moderately uniform texture, 2) a strong pebble fabric, consistent with the bedrock striations, and 3) stratigraphic position (in most cases) directly on the bedrock surface. Applying Boulton's (1976) criteria for distinguishing tills of different origin, the till facies of the Nashwauk Drift is the product of subglacial deposition, as a lodgement till. Other criteria supporting subglacial lodgement include its topographic expression, a gently undulating "ground moraine."

North of the Giants Range the Rainy Lobe was in an eroding mode. As evidence is the discontinuous drift cover over scoured and striated bedrock surfaces. To the south of the Range the glacier was in a depositional mode. Thick continuous deposits of pebbly till cover the region, the pebbles conspicuously local in origin.

North of the Giants Range, deposition is presumed to have occurred locally by lodgement as indicated by the patchy distribution of the Nashwauk till. Lodgement is a mechanical process whereby till is deposited from the sliding base of an active glacier (Dreimanis, 1982). The process is restricted to the thawed-bed zone, where the glacier is thick and the thermal gradient is low (Clayton and Moran, 1974). The frictional forces between a particle in traction and the bed become greater than the traction exerted by the moving ice. The particle becomes "lodged" or deposited on the bed (Boulton, 1972). Lodgement is a particle-by-particle process. Pressure melting of the flowing ice frees debris, allowing particles to be plastered, one-by-one, under pressure, onto the subglacial floor.

Irregularities on the lee side of a bedrock obstruction are filled in with till- a lee side till (Fig.11). The infilling provides an even contact between the bedrock and the glacier sole. Boulton (1971) has observed that where a debris-rich sole was moving in contact with bedrock, pressure melting led to the gradual release of detrital material. The lodgement process has masked much of the pre-existing topography, explaining the patchy nature of the Nashwauk till, and the smooth to gently undulating topographic expression.

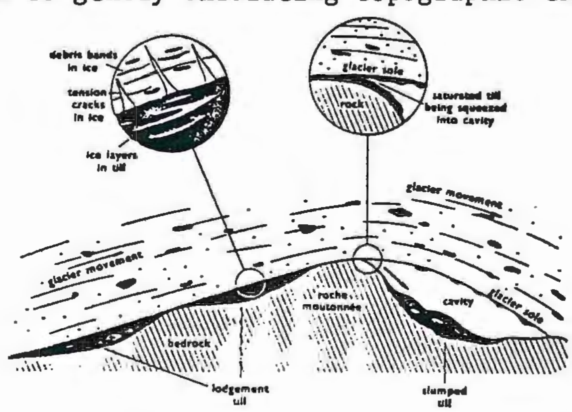


Figure 11. Deposition of Lee-side till accumulating at the base of Svalbard glaciers. (After Boulton, 1971).

CARIBOU DRIFT

General Characteristics

Deposits of the St. Louis Sublobe of the Des Moines Lobe dominate the western half of the field area (Fig. 7). The St. Louis Sublobe entered Minnesota from the west-northwest, depositing a brown silty till over previous Rainy Lobe deposits. In the study area, the bulk of the sediments deposited by the St. Louis Sublobe, here referred to as the Caribou Drift, consist primarily of stratified sand and gravel. Till occurs in the extreme west and northwest of the study area as a thin veneer on the highs of the collapsed topography. The till facies of the Caribou Drift has a mean sand:silt:clay ratio of 45:26:24. Composite results of the grain size analyses are presented on the triangular plot, Figure 12, and of the pebble orientation studies, Figure 13. In several localities outside the field area, fresh exposures of till were viewed. Fresh Caribou till is dark grayish-yellow (2.5YR4/2), and very blocky. Whitish-gray mottles of secondary carbonate commonly coat the joints or 'peds' of the blocky till, and frequently occur as secondary carbonate concretions.

Geomorphology

The St. Louis Sublobe landscape is characterized by collapse topography; high relief (over 45 meters) and steep angled slopes. Circular disintegration rings and ridges are abundant. Steep-banked, irregularly shaped lakes dominate the topography. The lakes occur in northeast-southwest trending arcuate trenches, separating higher areas of hummocky terrain. This phenomenon is best observed on the

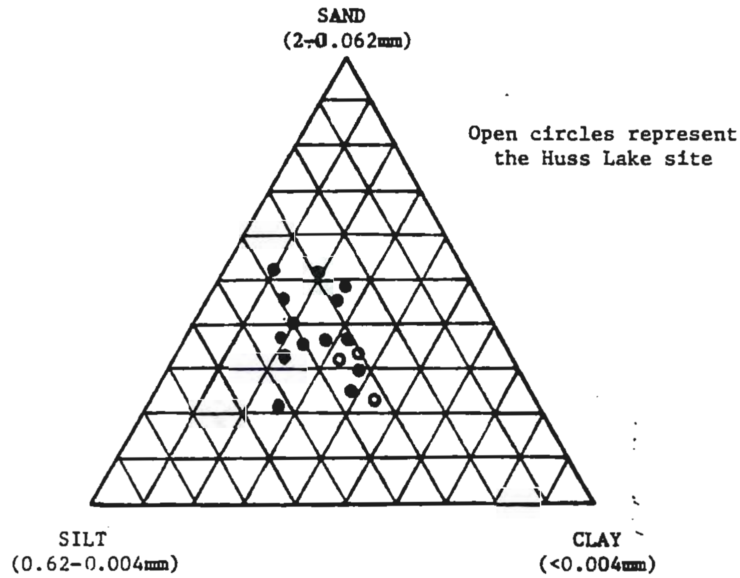


Figure 12. Grain size distribution for Caribou Drift.

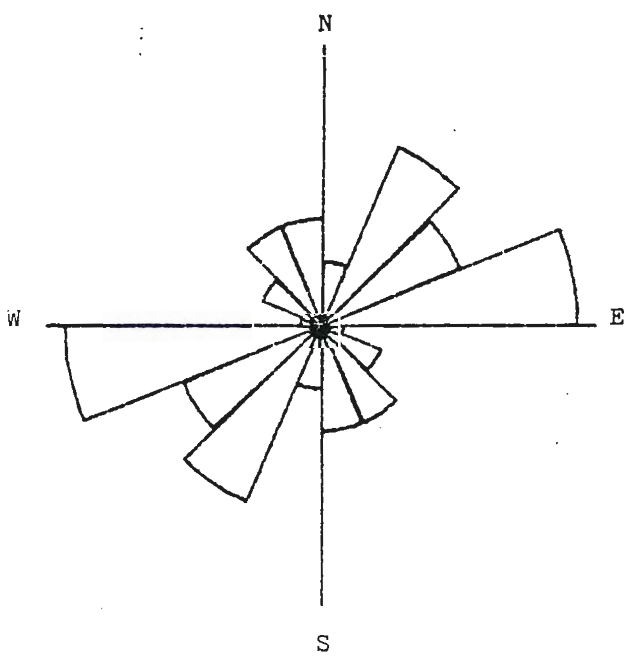


Figure 13. Caribou Drift Pebble Fabric
Total number: 46
Maximum per group: 12

Clubhouse Lake quadrangle. Parizek, (1969) has identified this type of topography as being deposited supraglacially, as a "controlled disintegration feature." As supraglacial debris melts out, concentric debris-rich bands are let down and reworked, resulting in oriented hummocky moraine.

In the northwestern region of the field area, the ruggedness of the topography lessens to a more subdued, undulating hummocky landscape. Boulders frequently occur on the surface, with a maximum diameter of one meter. The boulders are sub-angular to sub-rounded, and consist mostly of biotite schist. They were probably derived from outcrops of biotite schist along the Big Fork River, 10 km to the northwest.

Bordering this subdued topography on the south is a complex of eskers that extends the length of three quadrangles: Coon Lake, Balsam Lake, and Hartley Lake. The system heads in the Coon Lake quadrangle in a network of many coalescing individual eskers. A large esker extends southeastward from this junction, traceable for 20 km. For much of its extent, the esker is bordered on either side by lakes and swamps, e.g. Long Lake, Someman Lake, and Birch Lake. The esker terminates near Hartley Lake in an outwash fan. This position also marks the farthest extent of ice of the St. Louis Sublobe in the area.

The west-central portion of the field area topographically is a broad flat plain interrupted by many collapsed ice-block basins. Steep-banked lakes and swamps now occupy the basins. The plain, a pitted outwash plain, consists of a series of flat-topped hills grading from a high of 442 meters (1450 feet) in the west, to 411 meters

(1350 feet) in the east. This topography dominates the southern three-quarters of the Balsam Lake quadrangle, and the western half of the Hartley Lake quadrangle. The plain terminates at a distinctive topographic low: a meltwater channel marked by a chain of interconnected lakes. The lakes drain into the Prairie River, a tributary to the Mississippi.

Site-Specific Characteristics

The type section for the Caribou Drift is located near the western border of the field area, in the Clubhouse Lake quadrangle (18-59-25). Till occurs as a cresent-shaped cap, mantling a topographic high in the ice-contact sediment (Fig. 14). The unit is 2 meters thick in the center, pinching out in a concave downward direction with the slope of the hill. The unit is grayish-yellow colored (2.5Y6/2), very calcareous, and dried to a brick-like consistency. The sediment is matrix dominated, with no apparent sorting.

Clasts are dominantly granite (40%), metavolcanic and/or metasedimentary types (19%), limestone (13%), biotite schist (8%), and shale (3%). The clasts are angular, and few are tilted from horizontal. Most are concentrated towards the base of the unit. Pebble fabric is bimodal- transverse and parallel to ice flow direction. Transverse pebbles predominate. Because of the indurated nature of the sediment, a bias may have been introduced in both the stone count and orientation; data were collected only on pebbles exposed at the surface.

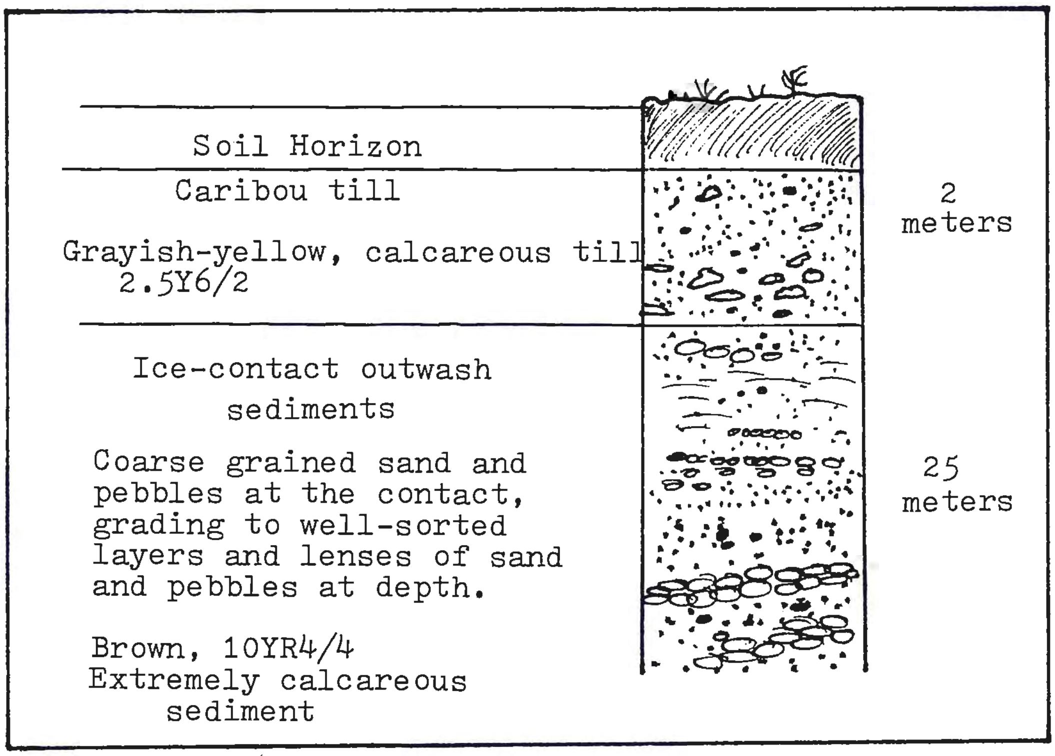


Figure 14. Stratigraphic section of Caribou till type section (Sec. 18, T59N, R25W).

The till facies of the Caribou Drift at the type location directly overlies ice-contact outwash sediments. The contact between the units is extremely sharp (Fig. 14). The outwash deposits consist of coarse-grained sand and pebbles, poorly sorted at the contact, grading to well-sorted individual lenses and layers. The sediment is extremely calcareous.

Deposits at the Huss Lake site (27-60-25) exemplify the nature of the sediment in the northwestern region of the study area. Exposed in a gravel pit near Huss Lake is a two meter section consisting of a fine-grained, well-sorted sand overlying a thin bed of till. The till overlies a sequence of coarse-stratified sand and gravel. The surficial sand consists of a very well-sorted, well-rounded non-calcareous sand, oxidized to a brown, 7.5YR4/4. No stratification is apparent. A layer of sand approximately 0.3 meter thick blankets much of the surface in this area, and is often capped by a pebble lag deposit.

The underlying till is approximately 0.3 meters thick, occurring at an elevation of 420 meters (1378 feet). The sediment is buff colored (10YR7/2), and calcareous. Clasts are sparse; dominant lithologies include limestone (57%), granite (33%), and shale (10%). Pebble fabric is bimodal, although dominantly northwest-southeast.

The underlying sediment consists of very calcareous cross-bedded coarse sand and pebbles. Pebbles range in size from 2mm to 2cm, and consist mostly of limestone. The floor of the pit is dominated by pebbles of limestone and shale, washed out from the overlying till.

A series of shallow roadcuts along Co. Rd. 345 has exposed a sequence of the materials characteristic of the flat-topped terrain of the east-central region. The sediment is dominantly coarse sand, interbedded with gravel and in some places lenses of silt. A pebbly sand generally forms the surface layer of the flat-topped hills. The sediment overall is well-sorted, and stratified with a diffuse planar bedding. The majority of the sediment ranges texturally from a pebbly sand to a very fine-grained sand, oxidized to a yellow-brown color (10YR5/6). The gravels are restricted to trough-shaped zones, and the silts to minor lenses. The sub-parallel strata range in size from 2 cm to 17 cm, the contacts marked by oxidation staining. Surface layers are non-calcareous, and leached well below the surface. Hand augering did not reach the unleached zones.

Drilling north of Antler Lake (Fig 6) in the same terrain, encountered a thick sequence of sand underlain by a stone-free silt which grades into a sparsely pebbly, calcareous sediment, which is very similar to that at the Huss Lake site. The silt is a stiff, yellowish-brown calcareous material, directly overlying the till. The contact between the two is gradational. Drilling penetrated the till, approximately a meter thick. Drilling at two other locations encountered till below the surface, at elevations of 411 meters (1350 feet) and 420 meters (1380 feet). In each case the tills are texturally and compositionally very similar to those found at the Huss Lake site. The sediment consistes of a sparsely-pebbly, poorly-sorted, very calcareous till. The sediment is gray, ranging from a 5Y4/1 to a 5Y5/1 moist Munsell color. Clasts are angular and broken (possibly due to the drilling). Lithologies include dominantly limestone, granite, and shale. The stone-free silt encountered at the Antler Lake drill site was not found overlying the till at any of the other drilling locations.

Depositional Environment

The western half of the field area represents the the furthest extent of the St. Louis Sublobe ice in northern Minnesota. The margin is characterized by thick (75 meters) supraglacial sediment, high relief (45 meters) steep slopes, and hundreds of ice-block basins. Their properties are all typical of a stagnant ice-disintegration complex.

Ablation of debris-rich ice has resulted in the accumulation of a thick cover of supraglacial sediment. Debris released in the terminal zone of the glacier was transported from the base by a strong upward component of flow. The texture and thickness of the supraglacial cover determines the rate of melting, and consequently the degree of sorting (Clayton and Moran, 1974).

Generally, supraglacial sediment is unevenly distributed over the surface of the ice, thus affecting its capacity to uniformly insulate. Ice that has a thinner supraglacial cover melts more quickly, forming depressions. Areas of thicker cover are left higher, generating mass movement on the newly formed slopes. Sediment moves down slope, filling the depressions, which then have a thicker supraglacial cover. The process repeats itself, resulting in topographic inversions

(Fig. 15).

The till facies of the Caribou Drift represents a sediment flow, or "flow till." The till occurs as a cap on highs of the inverted topography. The till is non-stratified and very poorly sorted. These properties suggest that the till has been "let down` with little available water in a stable supraglacial environment. Boulton (1971) refers to such a deposit as "autochthonous", the product of downslope creep.

The sharp basal contact and concentration of horizontal clasts towards the bottom of the sequence also support the hypothesis of a flow till. The pebble fabric poses a problem. The fabric of the Caribou till in general is consistantly bimodal, and primarily transverse to the ice-flow direction (Fig. 13). Compressive flow prevails in the terminal zone of a glacier, forcing the majority of blade-shaped stones to lie transverse to glacier movement. One would expect to find a transverse flow direction for stones at the Huss Lake site where the till represents a block of englacially derived material, as compared to the type locality, where the stone´s orientations should reflect the slope of the local topography. Boulton (1970) suggests a possible control on the fabric of a sediment flow to be the englacial fabric. The fabric of the Caribou till presumably reflects the englacial fabric, rather than the local slope direction.

The sediment underlying the till cap ranges from poorly sorted unstratified sands and gravel directly beneath the till, to well-sorted, planar bedded sands. These deposits represent the "washed" supraglacial debris and constitute the majority of the materials that

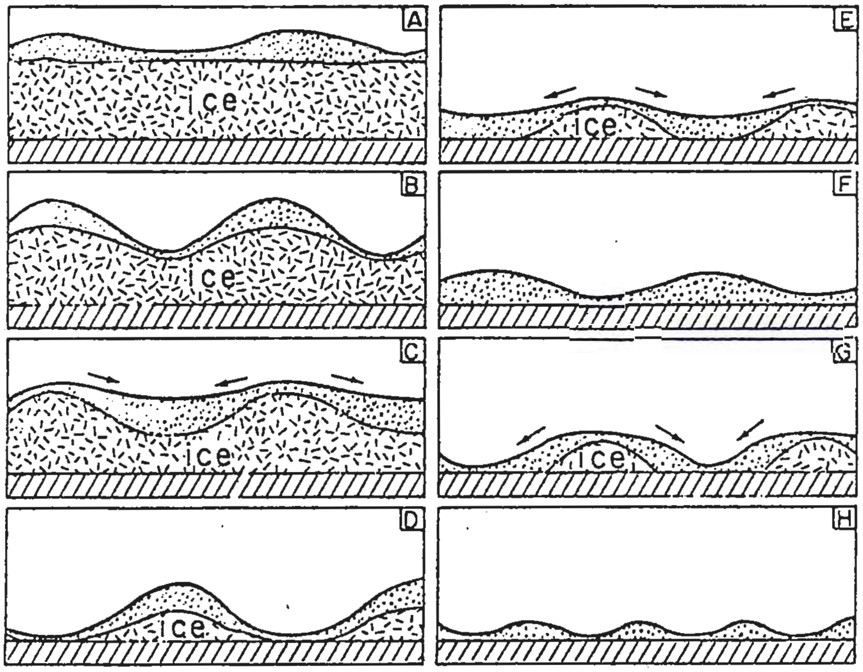


Figure 15. The Development of Supraglacial Till.
(After Clayton and Moran, 1971)

A. Non-uniformity of supraglacial sediment
B. Non-uniformity of insulation and melting
C. Mass movement
D. Inversion of topography
E,F Formation of hummocks
G,H Formation of circular distintegration ridges

makes up this suite. Fluvial activity in the area also produced thick supraglacial accumulations of stratified sand and gravel, occurring in the lower lying areas between the hummocks of supraglacial sediment. Fluvial deposits dominate towards the east, and are interpreted to be outwash discharged from the stagnant ice front. The area now is represented by a pitted outwash plain.

The lower-lying topography to the northwest is hummocky, although more subdued. Till, found both at the surface and encountered while drilling, occurs consistently at the same elevation. This till does not resemble the till at the type section in texture, stone lithology, or stone orientation. The till at the Huss Lake site is slightly finer grained, contains dominantly limestone pebbles (57% compared to 13% at the type section), and shows an orientation dominantly to the southeast. Its texture (considerably finer grained), and lithology (high percentages of limestone and shale) suggest an undiluted western source. Its occurrence consistently at the same elevation indicates a continuous unit. The lack of local bedrock, especially biotite schist, reinforces the intrepretation, and precludes a subglacial derivation. The Huss lake till and the till encountered while drilling probably represent a block or mass of englacially transported material melted out in the stagnant ice complex.

QUATERNARY HISTORY

Northern Minnesota was glaciated several times during the Quaternary Period, as indicated by the complex lithologies and stratigraphy of the glacial sediments. Multiple advances from the northwest, north, and northeast are evident, exposed in the deep open pits of the Mesabi-Vermilion Range area. Because of the lack of surface expression, these units have not been correlated to older drift units elsewhere, and are not well documented. Only the most recent episode of glaciation, the Wisconsinan, is well recorded.

Two till units of the Wisconsinan Stage are exposed in the report area, both laterally continuous, and, in places, each forms the surface unit. They represent deposits of the Rainy Lobe of the St. Croix Phase and the St. Louis Sublobe of the Alborn Phase of glaciation.

St. Croix Phase Glaciation

About 20,000 years ago, during the St. Croix Phase of glaciation, the Rainy Lobe began its advance through the report area. It advanced along an azimuth of approximately 225^{o}, as indicated by the glacial striations and drumlinized landforms in the area. Scoured and striated bedrock surfaces indicate that the glacier was actively eroding north of the Giants Range and depositing drift south of the Range. The Rainy Lobe advanced through the report area, and 325 km beyond to the south to form the St. Croix Moraine.

During the retreat of the Rainy Lobe in the study area, meltwater was ponded between the receding ice front and the topographic high of the Giants Range. Glacial Lake Norwood, a small glacial lake, was formed.

Drilling in the study area encountered interbedded fine silts and clays, presumably deposits of Glacial Lake Norwood. The lake sediment was encountered in two locations, both at approximately the 408 meters (1340 feet) level. This level approximately corresponds to the peat deposits in the floor of the Embarrass valley, the main body of Glacial Lake Norwood. Winter (1971) reports Glacial Lake Norwood attained an elevation of 442 meters (1450 feet), which would have inundated all but a very few bedrock highs of the study area, and would have given the lake a minimum depth of 34 meters (110 feet) in northeastern Itasca County.

The till facies of the Nashwauk Drift is considerably finer-grained as compared to typical bouldery Rainy Lobe drift. Presumably, a minor readvance of the Rainy Lobe over silts and clays of Glacial Lake Norwood produced the brown silty till, much the same as the readvances of the Superior Lobe produced the red clayey tills of the Split Rock and Nickerson Phases. The lack of evidence supporting a regional climatic fluctuation, and the non-synchroneity of other late Wisconsinan lobes has led Wright (1973) to believe that the readvances of the Superior Lobe in the Split Rock and Nickerson phases occurred as a series of glacial surges. Surging is the product of rapid and intense release of hydrostatic pressure behind a dam of debris-rich stagnant ice.

Till occurs along the northern flank of the Giants Range, confined to an elevation above 427 meters (1400 feet). Norvitch (1962) mapped the glacial deposits of the Nett Lake Indian Reservation, and came to the conclusion that St. Louis Sublobe Drift was not deposited above an altitude of 427 meters (1400 feet). A high kame deposit at 442 meters (1450 feet) in 3-64-22 consisted of Rainy Lobe material, in comparison to a lower kame, occurring at about 427 meters (1400 feet), in 34-65-21 that consisted entirely of materials deposited by the St. Louis Sublobe. The till facies of the Nashwauk Drift represents a remnant of a local readvance of the Rainy Lobe, protected by the highs of the topography along the northern flank of the Giants Range.

Following deglaciation of the St. Croix Phase, the Rainy and Superior Lobes readvanced to new positions. During the Automba Phase (Wright, 1972) the Superior Lobe moved out of the head of the Lake Superior basin, westward, to the vicinity of Mille Lacs Lake in east-central Minnesota. The Rainy Lobe advanced to a position just north of the study area, to the Vermilion Moraine. The Vermilion Moraine extends from the eastern end of the Mesabi Range, where it truncates the Toimi Drumlin Field, westward to Nett Lake in southern Koochiching County.

The Alborn Phase Glaciation

During the next period of glaciation (the late Wisconsinan Alborn Phase) the St. Louis Sublobe of the Des Moines Lobe advanced from the west-northwest into Minnesota via the Red Lakes Lowland of western Minnesota. Ice from the St. Louis Sublobe spread laterally eastward across the state. Wright (1972) has dated the advance at approximately 14,000 years. As the ice approached north-central Minnesota, the topographic barrier of the Giants Range caused the sublobe to split; part moving to the northeast and part to the southeast. Drift from that portion of the St. Louis Sublobe that moved to the southeast is red and clayey- a product of the incorporation of red lake clays. This is the Alborn Till of Baker (1964). To the north of the Range the drift is brown and silty- the character of its western source retained.

The St. Louis Sublobe ice extended eastward into the study area as far as Hartley Lake, where it stagnated. This occurred about 12,000 years ago. The terminal moraine consists of an ice stagnation complex, composed of a thick sequence of supraglacial sand and gravel, capped by a thin veneer of flow till. Total sediment thickness ranges from 15 to 75 meters. Considerable volumes of englacial material, exposed by a strong upward component of flow at the margin, wasted down to contribute to the supraglacial cover. Stratified sand and gravel added to the pile, a product of fluvial activity in the marginal zone.

During the meltout process, large blocks of ice were apparently stranded and later buried by outwash. These blocks melted out to form the kettle lakes and stagnation gravel deposits of the area, the fine-textured material being carried away by glacial meltwaters.

As the St. Louis Sublobe retreated from the area, meltwaters ponded between the ice front and higher topography to the east and south. A large shallow lake inundated the region, blanketing much of the area with a medium-grained, well-sorted sand, occurring at an elevation of just over 427 meters (1400 feet). The lake reportedly drained first down the Pike River Valley, across a divide near Embarrass, into the St. Louis River. As the ice to the south retreated enough to open a lower outlet, waters drained to the south. An abandoned meltwater channel, clearly marked by a series of interconnected lakes, occurs at the fringe of the margin of the St. Louis Sublobe ice. This channel drained by way of the Prairie River, a tributary to the Mississippi.

Finally, as ice of the St. Louis Sublobe retreated further north, Glacial Lake Agassiz proper developed. Glacial Lake Agassiz attained a maximum elevation of 414 meters (1360 feet), reaching as far east as Koochiching County, just to the north of the study area. Today much of what remains of Lake Agassiz are in the forms of extensive peatlands, covering much of northern Minnesota.

PHYSICAL COMPARISON OF THE DRIFT UNITS

The physical nature of the drift types is an important aspect of their use in exploration geochemistry. On an areal scale, the comparison is based on stratigraphic position, stratigraphic thickness, and areal extent, whereas texture, color, stone lithology and clay mineralogy were examined as a means of camparing their individual properties.

Stratigraphic Position, Thickness and Extent

The Nashwauk Drift is stratigraphically the lowest unit, occurring in the report area as a patchy basal till which is confined to topographic highs along the northern flank of the Giants Range. Deposits are thin and discontinuous, averaging a meter, and filling depressions in the irregular bedrock surface.

The Caribou Drift represents a complex of materials comprising an ice-disintegration complex. Total sediment thickness ranges from 15 to 75 meters. Stratified sand and gravel dominate the complex, which in the west is capped by a thin veneer of flow till. In the northwest is a more continuous layer of till that is interpreted to be the product of englacial meltout. Till of the St. Louis Sublobe in the area is represented by these two end members, whose texture, lithologies, and geomorphic setting differ. For the purposes of comparing St. Louis Sublobe Drift with drift of the Rainy Lobe, the samples have been combined.

Texture

Texturally, the two drift units are difficult to differentiate in the field. Because of their fine-grained nature, matrix samples were collected and analyzed in the laboratory. Results of the grain size analyses are presented on Figures 9 and 12.

A second method of analyzing textural differences in sedimentary units involves a comparison of various statistical parameters as revealed graphically from cumulative frequency curves. The graphic mean and median grain size, degree of sorting, skewness, and kurtosis, statistical measures used to quantitatively describe the curves, are presented for a summary for both till types (Table 2). Mean and median grain size range from a very fine sand in the Nashwauk till to a silt in the Caribou till. The Caribou till is texturally finer than the Nashwauk till. The median grain diameter (by weight) was determined directly from the 50th percentile of a cumulative frequency curve.

A third statistic, the inclusive graphic standard deviation, was used as a measure of the degree of sorting. The sorting formula (Table 1) includes 90% of the distribution and is the best overall measure of sorting (Folk, 1974). An inclusive graphic standard deviation of zero phi would indicate perfect sorting, and of 4.0 phi, extremely poorly sorted. Table 2 shows an inclusive graphic standard deviation of 4.05 phi for the Caribou till samples as compared to 3.63 for the Nashwauk samples. The Caribou till is more poorly sorted than the Nashwauk till.

Table 2. SUMMARY OF SEDIMENT CHARACTERISTICS

	NASHWAUK TILL	CARIBOU TILL
Median	3.3 phi (very fine sand)	4.5 phi (silt)
Graphic Mean	3.91 phi (very fine sand)	5.02 phi (silt)
Inclusive Standard Deviation	3.63 phi (very poorly sorted)	4.05 phi (extremely poorly sorted)
Inclusive Skewness	0.27 (positively skewed)	0.19 (positively skewed)
Graphic	1.4 (leptokurtic)	0.99 (mesokurtic)

Skewness is a measure of asymmetry of the curve. The inclusive graphic skewness (Table 1) includes 90% of the curve, taking the tails into consideration more so than the central portion. Symmetrical curves would yield a value of zero. Both the Nashwauk and Caribou till samples yield positively skewed distributions, with the Caribou till portraying a more symmetrical curve.

Kurtosis is a measure of the peakedness of the cumulative frequency distribution, used as a quantitative method to describe the departure from normality. It measures the ratio between the sorting in the tails of the curve and the sorting in the central portion. The Nashwauk till samples yield a kurtosis of 1.4; a leptokurtic curve implying that the central portion is better sorted than the tails. Caribou till samples display a mesokurtic curve, representing a more normal frequency distribution.

Color

In most instances, the Nashwauk and Caribou tills can be differentiated by color. The Caribou till samples are generally light brown to light-gray in color, with hues in the 10YR and 2.5YR range of the Munsell color system. Nashwauk till samples, brown to yellowish-brown in color, most often exhibit hues in the 10YR range.

Stone Lithology

The best method of differentiating the glacial tills in the study area is by the lithology of the stones within the tills. The Nashwauk till contains primarily granitic and metamorphic rocks of local origin, and also basalt, gabbro, red felsite, and granophyre. The red granophyre and distinct Lake Superior agate are especially important as indicators of a northeasterly source.

Although the Caribou till samples contain dominantly local bedrock types; it also has an average of 35% of stones that indicate a northwestern source: limestone, shale, and buff-colored chert. Sediment characteristics are summarized in Table 3.

Table 3. SUMMARY OF SEDIMENT CHARACTERISTICS

	NASHWAUK TILL	CARIBOU TILL
SOIL COLOR	10YR5/3	10YR6/4
GRAIN SIZE DISTRIBUTION sand:silt:clay (standard deviation)	60:23:12 (19:16:8)	45:26:24 (11:11:9)
PEBBLE LITHOLOGY (>4mm)		
granite	54%	44%
gabbro/diabase	11%	9%
basalt	16%	9%
granophyre	3%	<1%
agate	1%	<1%
iron formation	<1%	<1%
metased/volcanic	14%	8%
limestone	<1%	19%
chert	<1%	5%
shale	0%	3%
other	<1%	2%

Clay Mineralogy

The clay fraction from representative samples of both till deposits were X-rayed in an attempt to qualitatively assess mineralogical differences. The analysis was performed using a Picker Diffractometer with CuK_{α} radiation, from 3 to 30 degrees 2θ at a speed of one degree per minute (Larsson and Nickol, 1971; Moore 1968).

Ten samples were selected (5 from each till type) for the analysis. The clay size fraction of each sample was used in the analysis, collected during the pipetting procedure of the grain size analysis. Mineral identification was based on a series of 'standard' radiographs prepared in the laboratory, and from Chen (1977).

Quartz, feldspar, chlorite, and smectite were detected in the analyses, although the patterns from both till types were similar. Dean and Gorham (1976) qualitatively and quantitatively analyzed the clay mineralogy of surficial deposits across several midwestern states. They found no regional difference in the clay mineralogy. Arneman and Wright (1959) also found insignificant differences in the clay mineralogy of Minnesota tills. They concluded that clay mineralogy analysis was not particularly useful in the differentiation of Minnesota tills. Further attempts at X-ray analysis were not made.

PART II: GEOCHEMISTRY AND GEOSTATISTICS

Introduction

Part II of this investigation involves the chemical characterization of the two drift types. A traverse bisecting the two drift types was chosen for geochemical sampling. Groundwater, lake water and lake sediment were selected as the geochemical sampling media. It has been found (Boyle, (1979); Brugam, (1981); Coker and others, (1979); Dean and Gorham, (1976); Miller, (1979)) that these media reflect the regional geology, with the weathering of rocks and soils of the encompassing drainage basin, and more importantly, the local geology, that is the materials with which these media have direct contact. This consitutes the fundamental basis for all geochemical surveys. Conductivity, pH, loss-on-ignition, and ten elements were chosen as the parameters to depict the chemistry. The chemical characterization and comparison involves the statistical analysis of these parameters.

The chemistry of a groundwater and/or lake system is the product of various physical, chemical, and biological factors. The interaction of these factors directly influence the nature of the constituents of natural waters. Eh and pH are thought to be the dominant controls on elements in the surficial environment, they govern the solubilities of elements, and serve to characterize the variables in terms of the surficial environment.

Typical surficial conditions involve an oxidizing and slightly acidic environment. Most elements are soluble and mobile under these conditions. The relative mobilities of the elements of interest to this investigation are presented in Table 4.

Table 4 RELATIVE MOBILITY OF ELEMENTS IN THE SURFICIAL ENVIRONMENT (Modified from Levinson, 1974)

MOBILITY	OXIDIZING	REDUCING	ACID	NEUTRAL TO ALKALINE
MODERATELY MOBILE	Ca,Na,Mg Zn	Ca,Na,Mg	Ca,Na,Mg, Zn,Co,Cu,Ni	Ca,Na,Mg
SLIGHTLY MOBILE	K Co,Cu,Ni	K Fe,Mn	K Fe,Mn	K Fe,Mn
IMMOBILE	Fe,Mn	Co,Cu,Ni,Zn	-	Co,Cu,Ni,Zn

Mobilities vary considerably according to specific environmental conditions. Eh and pH are dominant controls, although adsorption, organic matter, temperature, and many other factors can influence the existence and concentration of elements in the surficial environment. Levinson (1974) suggests nine other factors that must be considered as potentially important influences on the mobilization, transportation, and accumulation of metals in the surficial environment: 1) nature of the medium, 2) mechanism of transport, 3) composition of country rock, 4) presence of microorganisms, 5) solubility of salts, 6) formation of complex ions, 7) membrane effects, 8) the presence of dissolved gases, and 9) mechanical factors (porosity, permeability, etc.).

Sampling and Analytical Techniques

Well Water

Seventeen wells were selected in this investigation to represent shallow glacial drift aquifers across both drift types (Fig. 16). Procedures for sampling followed the guidelines published in Ferguson and others (1977). Samples were taken exclusively from untreated, private, domestic wells older than six months in age. Well type, depth, age, pipe composition, and frequency of use were recorded at each site. Depth measurements were based on the depth of the drilled or augered well, not the actual water level. Samples were taken as close to the wellhead as possible, usually at an outside faucet. After running the pump for 2-3 minutes to flush the system, two water samples were collected. The first, for pH and conductivity measurement, was rinsed then refilled directly from the tap. Conductivity was measured using a Myron field conductivity meter, from a portion that was set aside and allowed to equilibrate to ambient temperature. To obtain specific conductance, all measurements were temperature corrected. A portion of this sample was also retained for pH measurement in the laboratory. A second sample was collected to analyze for metals. Water was collected in acid-cleaned and pre-rinsed plastic vials, filtered, using 0.45 um Millipore filter paper and a Millipore filtering apparatus, then immediately acidified with 0.1 ml concentrated HNO_3 to keep the metals in solution (Levinson, 1974). Samples were immediately placed in a cooler, and kept chilled until the analysis, which was completed within three days of sampling.

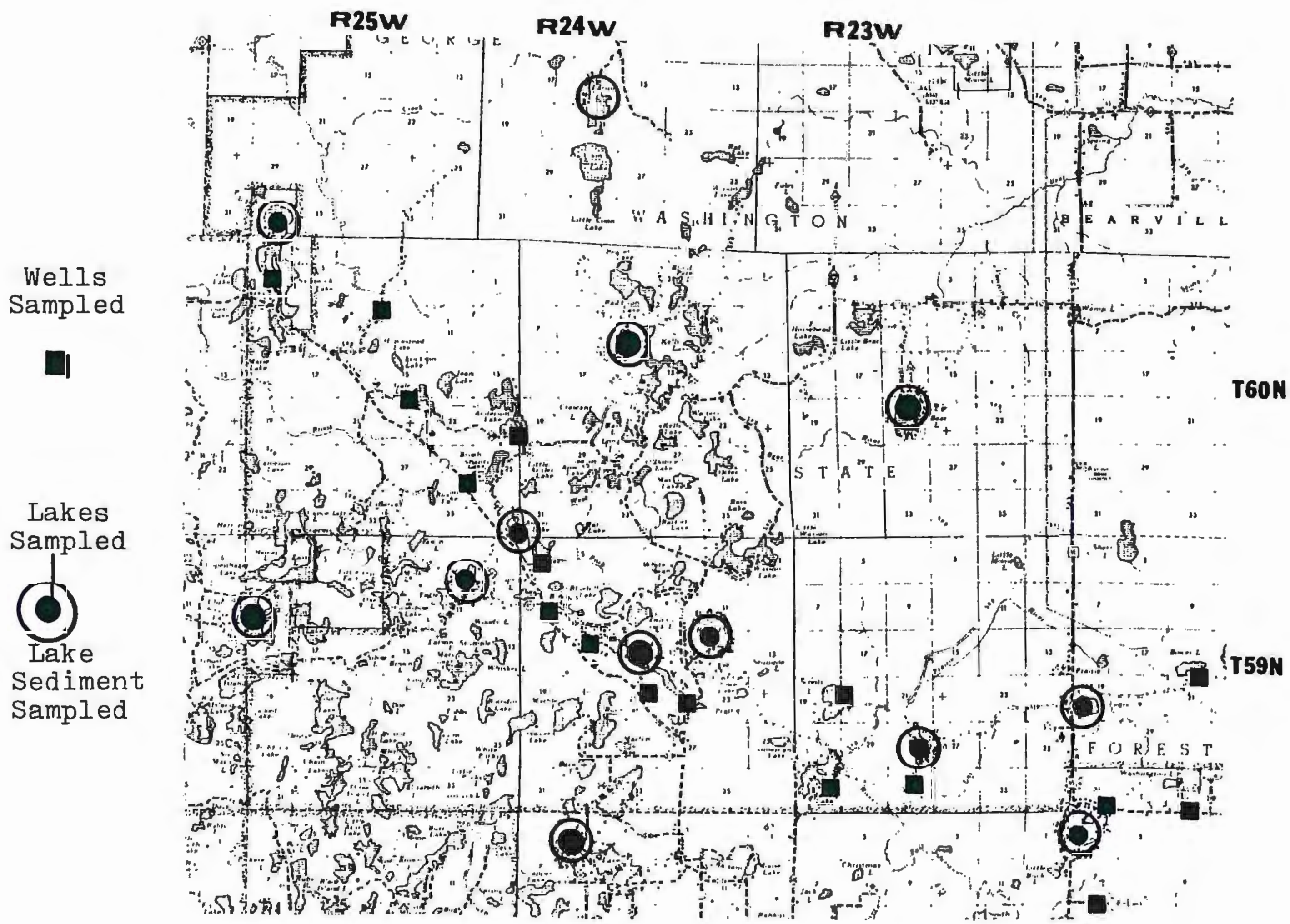


Figure 16. Location Map for Study Wells and Lakes.

Lake Water

Twelve lakes were sampled for the investigation, eight by the author and four by the DNR in a previous investigation (DNR project 71-3, 6-1977, Fig. 16). Lakes were selected to represent those with groundwater input. The lakes ranged in depth from 7 to 95 feet, with an average of 35 feet. Hawkinson and Verry (1975) have adopted a system of classification which relates specific conductance to the degree of groundwater input. Their study, conducted in central Itasca County, separated lakes into three categories: perched (above the water table), groundwater, and transitional. The specific conductivity for groundwater lakes in their investigation ranged from 144-192 umhos. The conductivities for lakes in this investigation ranged from 30-165 umhos, with five of the eight sampled by the author being classified (according to Hawkinson and Verry) as having a a significant input from the groundwater flow system. Conductivity was not measured in those lakes sampled by the DNR.

In Hawkinson and Verry's classification of lakes, groundwater lakes contain a high concentration of dissolved materials, particularly calcium, and consequently yield a high conductance. Although specific conductance can be used as a general guide to the degree of groundwater input, seasonal variations occur.

Lake water sampling was done in August, 1981, before the fall turnover period (about October). The samples were collected from the hypolimnion, the cold undisturbed bottom region of the lake. The hypolimnion of eutrophic lakes is generally reducing, and the concentrations of the minor metals (with the exception of nickel) are significantly higher (Levinson, 1974, Figure 17). An electronic depth finder was used to locate the deepest area of the lake, and to determine depth at each sample site.

Water sampling was done from a boat, using a Kemmer plastic water sampler. Two samples were taken from the sampler, one for pH and conductivity, and one for laboratory analysis of the elements. Cleaned and rinsed 100 ml plastic vials were used. The sample that was to be analyzed for element concentrations was filtered and acidified, as were the groundwater samples, and stored in a cooler prior to analysis.

Lake Sediment

Organic-rich sediment was collected from eight lakes sampled by the author and from five lakes by the DNR in a previous investigation. Sampling was accomplished with a gravity-driven core sampler. The sampler consists of a 5cm diameter plastic inner tube which is retained by an outer steel pipe. The sampling tube is 47 cm in length. The sampler is designed to collect (except for compaction) a relatively undisturbed vertical section of lake sediment.

The lake sediments sampled by the author were collected in March 1982 when ice still covered the lake. This provided easier access for sampling. Samples were taken from the deepest portion of each lake. The sampler was lowered by a rope, and when returned to the surface, the plastic inner liner of the sampler could be removed. Typically, 15 to 20 cm of gyttja were retained in the sampler. Gyttja is the term used to describe the reworked organic and inorganic material of

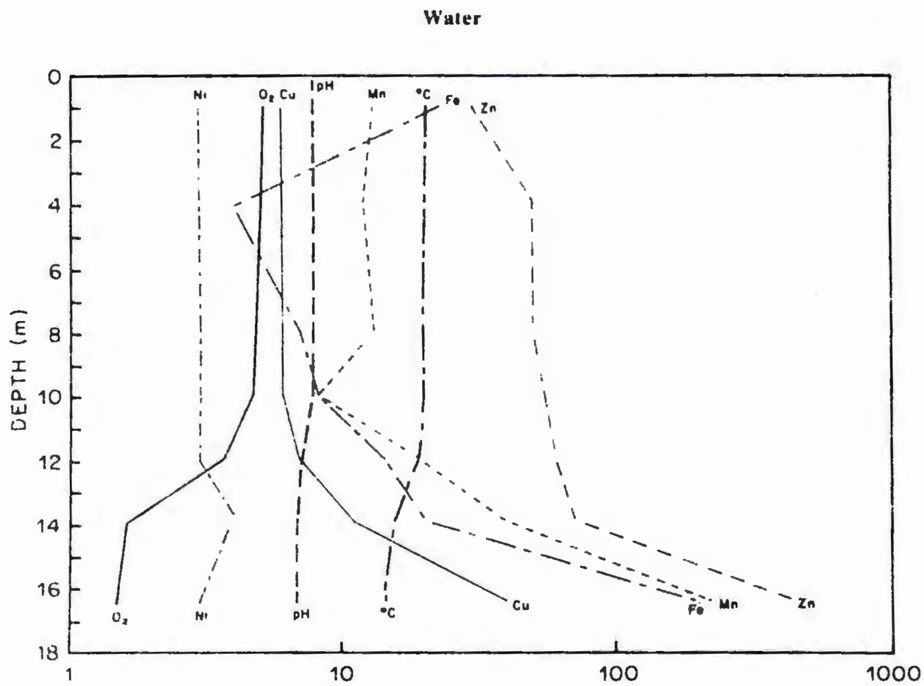


Figure 17. Vertical Profiles (obtained during the summer) of dissolved oxygen, pH, temperature, and metal contents (ppb) in water at Lake Athapapuskow, Saskatchewan. (Levinson, 1974).

the lake bottom. It forms a very characteristic gray to brown-black, finely divided sediment with a gel-like consistency. It is found in organic rich lakes where there is a deciduous-coniferous forest cover. It typically has a strong H_2 odor, indicating reducing conditions. conditions. Each 15 to 20 cm of sediment represents a composite sample, and therefore should not be greatly affected by seasonal variations in the lake chemistry (Vadis and others, 1982). The top 50 mm of sample were discarded to avoid both recent contamination and the products of oxidation-reduction at the sediment-water interface. The sample collected is generally a reduced sample, as indicated by the presence of the strong H_2S odor.

Water color, water depth, shoreline vegetation, topography and glacial deposit type were recorded for each sample site, when available. The degree of H_2S odor and the color and texture of the gyttja were recorded for each sample.

Samples collected by the DNR (project 71-3, 6/1977) were sampled in June, 1977. Four different sites within each of the five lakes were sampled to include major bays and basins as well as inlets and outlets. The lakes sampled are shown on Figure 16. Collection techniques and analytical procedures for those samples (both lake water and lake sediment) collected by the DNR have remained essentially the same, except for oven-drying the samples rather than presently freeze-drying (refer to page 62).

Sample Analysis

Laboratory analyses were performed by Suanne Dullard and Al Klaysmat, chemists for the Minerals Division of the Minnesota Department of Natural Resources, Hibbing, Minnesota. Soil and water pH were measured in the laboratory, using an Orion digital pH meter with a Ross electrode. A Perkin-Elmer (model 603) atomic absorption spectrophotometer was used to measure the concentrations of all elements for water and lake sediments.

Analyzing for Trace Metals (Cu,Ni,Co,Zn) in Water Samples

Each water sample was filtered and acidified with 0.01 ml concentrated HNO_3 at the time of sampling and refrigerated prior to analysis. Samples with element concentrations greater than 0.01 ppm were analyzed by the flame method on the atomic absorption spectrophotometer (AA), and those with concentrations less than 0.01 ppm were analyzed using the graphite furnace.

Analyzing for Major Metals (Na,K,Mg,Fe,Mn,Ca) in Water Samples

Samples being analyzed for Ca,Mg, Na, and K were diluted 20 times in a volumetric flask with doubly distilled water (distilled then deionized) and 15 mls of lanthanum chloride (LaCl). The LaCl reduces background ionization for samples being analyzed on the AA. The concentrations of the ions in the samples were generally all greater than 0.01 ppm, so the flame method (see appendix A) of analysis was used. Iron and manganese require no dilution. These elements were also analyzed by the flame method.

Analyzing for Trace Metals (Cu,Ni,Co,Zn) in Lake Sediments

Each sample was freeze-dried and sieved on a -80 mesh stainless steel sieve. A 0.5 gram sample of the finer that -80 mesh fraction was used in the analysis; 7.5 ml each of 4N HNO_3 and 1N HCL were added to each sample. The samples were mixed and then heated to 90°C, and held at that temperature for two hours. The digested samples were diluted 50 times in doubly distilled water, and then analyzed by the flame method on the AA.

Analyzing for Major Metals (Na,K,Mg,Fe,Mn,Ca) in Lake Sediment

Each sample was freeze-dried and the -80 mesh size fraction retained, 0.2 grams of which was placed in a crucible and oven-dryed. The samples were heated at 500°C for 5 hours, to burn off any organic material that may interfere with the analysis. After being "ashed" the samples were transferred to teflon crucibles and 1 ml each of concentrated HF, HCl, and HNO_3 was added to each. The teflon crucibles were placed in an acid bomb and the samples are heated for one hour at 100°C. The acid bomb adds pressure as well as heat to the digestion. Following digestion the samples were cooled and 3.2 grams of boric acid were added to each. The samples were transferred to a 100 ml volumetric flask and brought to volume with doubly distilled water. Samples were stored in a polyethylene container prior to the analysis.

Analytical Precision

Analytical precision for the water samples was determined by replicate analyses of randomly selected samples, followed by a statistical comparison. In addition to the replicate samples, each analytical batch of 20 samples contained a duplicate. Results for each of the duplicate analyses are presented with the analytical data.

The analytical precision for lake sediment samples was accomplished by two methods. The first method was to analyze a cut from a precision lake sediment sample with each analytical batch of 20 samples. From these samples, analytical precision was calculated at the 95% confidence level. The second method used involved the re-analysis of two sets of lake sediment samples with each analytical batch. The analytical precision was calculated by a method adapted from Garrett (1969, 1973). Results of the the calculations of analytical precision for these samples are shown on Table 5.

The analytical detection limits for each of the elements analyzed using the flame method is 0.01 ppm, and using the furnace, 0.001 ppm. In most cases the concentrations grossly exceed the detection limit, however those samples below the detection limits are given in parenthesis with the results.

Table 5. Analytical Precision for Lake Sediment Samples

Element	Analytical Results	Acceptable Mean	Acceptable Range	% Precision
Cobalt	10ppm	9.5	6-13	72%
Copper	20ppm	20.5	14-27	62%
Nickel	35ppm	39.0	31-47	40%
Zinc	105ppm	83.5	71-96	30%
Iron	1.45%	1.19	.89-1.49	13%
Manganese	4.6%	4.43	3.98-4.87	20%
L.O.I.	39.90%	38.29	34.46-42.12	20%

*The acceptable values were determined from four years of data, calculated using the selected percent in the table below and the mean from the data.

THE DATA

Results of the chemical analyses of lake water, well water, and lake sediment are given in Tables 6, 7 and 8. Preliminary inspection of the raw data set was performed to: (1) detect anomalous cases and variables, 2) determine interrelationships among the data, and 3) make generalizations concerning the populations. "Preconditioning" is necessary not only to reduce the data into scientifically acceptable form but also to aid in the selection of the statistical tests to be used in the analysis.

Well Water

Results of the chemical analysis for well samples are listed in Table 6. The element concentrations are recorded in parts per million, with those concentrations below the analytical detection limits given in parentheses. Group range, median, mean and standard deviation are listed in Table 9.

Some data were eliminated prior to the statistical analysis. For example, the concentration of cobalt is consistently at or below the analytical detection limit (0.001 ppm) of cobalt for each of the samples. Because of this, cobalt would prove irrelevent to any statistical analysis, and consequently, was eliminated.

The concentration of copper in the Caribou Drift samples like those of cobalt, are at or very near the analytical detection limit. The mean copper concentration in the Nashwauk Drift samples, however, is significantly higher, indicating perhaps significant group

TABLE 6 Results of Chemical Analysis for Study Wells

SAMPLE NUMBER	DEPTH (ft.)	pH	SPECIFIC CONDUCTIVITY (μho×100)	Co (ppm)	Cu (ppm)	Ni (ppm)	Zn (ppm)	Fe (ppm)	Mn (ppm)	Ca (ppm)	K (ppm)	Mg (ppm)	Na (ppm)
Rainy Lobe (Nashwauk Drift)													
07	20	6.5	–	(.001)	(.001)	.110	0.50	12.60	0.08	10.00	2.00	6.00	8.00
08	22			.001	.005	.011	0.37	0.29	0.01	4.00	3.00	1.00	7.00
09	20	5.7	5.00	.003	(.001)	.019	0.67	0.10	0.03	35.40	3.20	11.00	18.40
12	25	5.9	2.05	.001	.013	.010	0.03	0.43	0.04	12.40	1.40	6.20	12.80
13	40	6.1	0.50	.001	.057	(.001)	0.14	0.07	0.01	3.00	0.80	1.40	5.40
14	447	8.6	7.50	.003	(.001)	.004	0.07	0.02	(0.01)	5.20	1.00	1.80	33.60
15	120	8.0	4.00	.001	.002	.027	0.05	0.82	0.06	46.40	1.80	16.40	6.80
St. Louis Sublobe (Caribou Drift)													
16	29	7.6	2.20	(.001)	.001	.016	0.20	2.83	0.33	33.40	1.00	6.80	2.80
17	14	6.8	1.80	.001	.057	.012	3.24	0.53	0.03	15.40	0.80	7.40	3.80
18	96	7.0	1.70	.001	(.001)	.007	0.63	15.25	0.20	14.80	1.40	5.60	2.60
19	63	7.7	3.00	.001	(.001)	.018	0.04	0.03	(0.01)	36.20	1.40	11.80	3.80
20	76	8.0	2.10	.001	(.001)	.014	0.02	0.31	0.17	26.60	1.80	5.60	6.60
21	120	7.8	3.40	.001	(.001)	.015	0.01	0.74	0.38	35.20	2.40	11.60	10.00
22	50	7.4	5.00	.001	(.001)	.017	0.15	0.50	0.11	63.00	1.60	21.00	6.60
23	30	7.4	7.00	.001	(.001)	.019	0.10	2.21	0.27	86.20	2.80	45.00	10.40
24	120	7.5	6.00	.001	(.001)	.014	0.12	0.02	0.43	69.80	3.00	23.20	9.20
25	15	7.2	3.20	.001	.005	.018	0.12	0.11	0.45	43.40	2.20	11.40	3.20
41	21	8.0		(.001)	(.001)	.020	0.40	0.30	0.18	34.00	2.00	2.00	6.00
43	19	8.0		(.001)	(.001)	.070	0.09	0.38	0.20	36.00	2.00	6.00	6.00

() Samples with concentrations below the analytical detection limits.

TABLE 7 Results of Chemical Analysis of Study Lakes

NAME	DEPTH (ft.)	pH	SPECIFIC CONDUCTIVITY (μhos x100)	Co (ppm)	Cu (ppm)	Ni (ppm)	Zn (ppm)	Fe (ppm)	Mn (ppm)	Ca (ppm)	K (ppm)	Mg (ppm)	Na (ppm)
Rainy Lobe (Nashwauk Drift)													
2 Wolf Lake	07	7.1	0.90	(.001)	.002	.002	.005	1.62	0.03	12.00	1.80	4.80	3.80
20 Wolf Lake Duplicate	07	7.1	1.00	(.001)	.002	.002	.004	1.26	0.07	12.20	3.00	10.60	4.00
10 Buck Lake	33	7.2	1.20	(.001)	.003	(.001)	.015	1.07	1.86	10.60	1.20	4.00	2.60
11 O'Leary Lake	16	7.6	0.30	(.001)	.017	(.001)	.023	0.03	0.03	1.60	0.40	5.20	1.00
50 * (DNR) Lost Lake	25	8.2											
51 * (DNR) Bear Lake	14	7.7		(no data obtained)									
St. Louis Sublobe (Caribou Drift)													
3 Round Lake	28	7.4	0.60	(.001)	.002	(.001)	.005	0.02	(.010)	5.40	0.60	2.20	3.00
5 Coon Lake	33	7.4	0.85	(.001)	.005	(.001)	.011	0.03	(.010)	9.20	0.80	4.40	1.00
7 Antler Lake	80	6.9	1.60	(.001)	.004	.003	.004	0.01	(.010)	17.60	1.60	5.60	5.60
37 Long Lake	22	6.7	1.35	(.001)	.005	.003	.011	0.41	(.010)	14.80	1.00	4.80	3.00
9 Antler Lake Duplicate	80	6.9	1.60	(.001)	.005	.006	.003	0.01	(.010)	18.60	1.40	5.20	5.40
39 Eagle Lake	30			.001	.005	.001	.027	0.08	(.010)	14.00	2.00	2.00	2.00
49 * (DNR) Clubhouse Lake	95	8.3											
52 * (DNR) Balsam Lake	27	8.5											

() Samples with concentrations below the analytical detection limits.
* Sampled by the Department of Natural Resources, Minerals Division, Project 71-3, 6-13-77.

TABLE 8 Results of Chemical Analysis of Lake Sediment Samples

NAME	SAMPLE NUMBER	pH (Sed. & H_2O)	DEPTH (ft.)	Co (ppm)	Cu (ppm)	Ni (ppm)	Zn (ppm)	Fe (wt. %)	Mn (wt. %)	Ca (wt. %)	K (wt. %)	Mg (wt. %)	Na (wt. %)	LOI (%)
Nashwauk <u>Drift Samples</u>														
Larson Lake	3907	8.4 7.0	113	13	12	22	59	0.71	0.736	0.70	0.32	0.48	0.14	33.40
" "	3908	8.4 7.0	55	11	12	16	50	3.99	0.220	0.60	0.45	0.46	0.17	37.60
" "	3909	8.4 7.0	55	12	12	20	64	1.87	0.653	1.02	0.49	0.72	0.20	37.40
Lost Lake	3913	8.2 6.6	25	9	13	13	81	9.30	0.325	1.32	0.44	0.27	0.18	51.50
" "	3914	8.0 6.5	25	10	13	12	82	9.00	0.341	0.23	0.46	0.27	0.19	50.30
" "	3915	8.2 6.4	21	9	14	15	75	9.40	0.363	0.34	0.41	0.26	0.16	50.40
Bear Lake	3916	7.5 6.5	13	20	14	25	244	1.01	0.107	0.12	0.85	0.48	0.39	40.70
" "	3917	7.7 6.6	12	20	14	25	247	8.70	0.125	0.12	0.86	0.45	0.39	39.90
" "	3918	7.8 6.7	11	21	14	26	240	9.30	0.120	0.13	0.87	0.44	0.44	37.90
Buck Lake	10725	7.4 6.3	27	10	32	23	81	1.96	0.060	0.56	1.13	0.73	0.88	36.71
O'Leary Lake	10726	7.5 6.3	20	7	18	17	60	0.59	0.025	0.49	0.63	0.37	0.32	64.47
Wolf Lake	10727	7.3 6.1	7	14	13	23	141	2.75	0.100	0.62	0.61	0.52	0.62	30.82
Caribou <u>Drift Samples</u>														
Clubhouse Lake	3910	8.4 6.7	95	8	8	8	27	1.01	4.900	2.26	0.22	0.19	0.12	37.90
" "	3911	8.0 6.6	67	9	9	12	33	1.24	3.800	1.42	0.28	0.21	0.13	38.60
" "	3912	8.3 6.9	85	10	10	15	30	4.00	1.016	0.72	0.35	0.39	0.16	37.50
Balsam Lake	3919	8.3 6.5	28	9	14	18	53	7.50	0.270	0.35	0.57	0.34	0.29	44.90
" "	3920	8.5 6.6	26	10	12	18	54	11.30	0.315	0.40	0.43	0.27	0.19	46.10
" "	3921	8.6 6.4	31	6	8	9	44	5.90	0.353	1.77	0.26	0.15	0.13	39.90
Long Lake	10728	7.4 6.3	9	7	23	16	65	4.80	0.135	0.84	0.59	0.65	0.41	57.53
Round Lake	10729	7.7 6.4	20	6	17	16	62	0.82	0.035	0.57	0.75	0.60	0.55	59.60
Coon Lake	10730	7.7 6.2	21	7	14	17	69	1.02	0.060	0.82	0.68	0.55	0.31	64.17
Antler Lake	10731	8.0 6.6	42	4	10	7	52	1.08	0.050	0.95	1.53	0.31	1.48	10.56
Eagle Lake	10732	7.8 6.7	17	13	22	24	127	3.70	0.165	0.93	0.52	0.58	0.37	60.10

TABLE 9 WELL WATER STATISTICS

Nashwauk Drift (N=6)

	Range	Mean	Standard Deviation	Median
pH	5.7-8.6	6.4	0.9	6.1
Depth	20-120	41.17	39.35	25
SPCOND	0.50-7.50	2.9	2.0	3.0
Cobalt	0.001-0.003	0.001	.001	0.001
Copper	0.001-0.057	0.013	0.022	0.004
Nickel	0.001-0.027	0.030	0.040	0.015
Zinc	0.03-0.67	0.29	0.26	0.26
Iron	0.02-12.60	2.39	5.01	0.36
Manganese	0.01-0.80	0.16	0.31	0.04
Calcium	3.00-46.40	18.5	18.0	11.2
Potassium	0.80-3.20	2.03	0.92	1.90
Mangnesium	1.00-16.40	7.0	5.89	6.10
Sodium	5.40-18.40	9.73	4.95	7.50

Caribou Drift (N=12)

	Range	Mean	Standard Deviation	Median
pH	6.8-8.0	7.5	0.4	7.6
Depth	14-120	54.4	40.1	40
SPCOND	1.7-7.0	3.54	1.85	3.10
Cobalt	0.001-0.001	0.001	0	0.001
Copper	0.001-0.057	0.006	0.016	0.001
Nickel	0.007-0.070	0.020	0.016	0.017
Zinc	0.01-3.24	0.43	0.90	0.12
Iron	0.02-15.25	1.93	4.29	0.44
Manganese	0.01-0.45	0.23	0.15	0.20
Calcium	14.80-86.20	41.16	21.53	35.60
Potassium	0.80-3.00	1.87	0.67	1.90
Magnesium	2.00-45.00	13.11	11.86	9.40
Sodium	2.60-10.40	5.92	2.79	6.00

TABLE 10 LAKE WATER STATISTICS

Nashwauk Drift (N=5)

	Range	Mean	Standard Deviation	Median
pH	7.1-8.2	7.6	0.4	7.6
Depth	7-33	19	10.1	16
SPCOND	0.30-1.20	7.6	0.44	1.20
Cobalt	0.001-0.001	0.001	0	0.001
Copper	0.002-0.017	0.007	0.008	0.003
Nickel	0.001-0.002	0.001	0.001	0.001
Zinc	0.005-0.023	0.014	0.009	0.015
Iron	0.03-1.62	0.907	0.807	1.07
Manganese	0.03-1.86	0.64	1.06	0.03
Calcium	1.60-12.00	8.07	5.64	10.60
Potassium	0.40-1.80	1.13	0.70	1.20
Mangnesium	4.0-5.20	4.67	0.61	4.80
Sodium	1.0-3.80	2.47	1.40	2.60

Caribou Drift (N=7)

	Range	Mean	Standard Deviation	Median
pH	6.7-8.5	7.5	0.7	7.4
Depth	22-95	45	29.5	30
SPCOND	0.60-1.60	1.1	0.46	1.48
Cobalt	0.001-0.001	0.001	0	0.001
Copper	0.002-0.005	0.004	0.001	0.005
Nickel	0.001-0.003	0.002	0.001	0.001
Zinc	0.004-0.027	0.012	0.009	0.011
Iron	0.01-0.41	0.11	0.17	0.03
Manganese	0.01-0.01	0.010	0	0.010
Calcium	5.40-14.80	12.20	4.86	14.0
Potassium	0.60-2.0	1.20	0.58	1.0
Mangnesium	2.0-5.60	3.80	1.61	4.40
Sodium	1.0-5.60	2.92	1.71	3.0

differences; therefore, copper was left in the statistical analysis.

Several anomalous values were measured at site 14, i.e., low concentrations of nickel, zinc, iron, and manganese, higher than average concentrations of sodium and cobalt, and an unusual depth measurement of 136 meters. This is much deeper than the surrounding wells. The values measured for each variable are representative of waters whose aquifers are Lower Precambrian metamorphic rocks, not the glacial drift with which this investigation is concerned. Sample 14 was consequently eliminated from the data set that was to be used in the statistical analysis.

The range of concentrations of the minor metals (Table 9) copper, nickel, zinc and manganese is very small, as indicated by their small standard deviations. Iron has a standard deviation of 5.01 for Nashwauk Drift samples, and 4.29 for Caribou Drift samples. One anomlous measurement occurs in the Caribou Drift analysis, 12.6 ppm (sample 7) among an average value of 1.93, however, the values measured on each of the other variables were not anomalous, so sample 7 was not deleted from the statistical analysis.

The distribution of calcium concentrations in the Nashwauk Drift samples appears to be bimodal, with several small (3, 4, and 5 ppm) and several large (10, 12, 35, and 46 ppm) measurements. The distribution is recorded on Table 9, with a mean of 18.5 ppm and a standard deviation of 18 ppm. Magnesium and sodium also show sporadic distributions with unusually high deviations. Krumbein and Graybill (1965) suggest that sporadic large deviations are expected in log-normal data, and especially in geochemical data where large deviations may be indicators of mineralization. In light of this, the distribution patterns of each of the other variables, (and cases) were acceptable, and were entered into the statistical analysis.

Lake Water

Results of the chemical analysis of lake data are given in Table 7. Lakes are divided on the basis of drift type, with those sampled by the DNR (Meineke and others, 1977) indicated by an asterisk. Group range, median, mean, and standard deviation for each element are given in Table 10.

Cobalt concentrations in the lake water analysis, like those of the well water analysis, are uniform, and with the exception of two cases, all are at or below the analytical detection limit for cobalt (0.001 ppm). Cobalt was eliminated as a variable from the lake water statistical analysis. Manganese concentrations in the Caribou Drift samples are also uniform, consistently at or below the analytical detection limit (0.001 ppm). However, within the Nashwauk Drift samples, several high (greater than 1.0 ppm) values have been recorded. This may suggest possible differences between drift types. The high values correspond to the deepest Nashwauk Drift lakes. The differences observed in the metal concentrations between drift types probably represent oxidation reduction reactions rather than actual chemical differences, although manganese was left in the analysis.

The range of the concentrations of each of the other metals is small, as indicated by their standard deviations. There are no anomalously high values, and nothing was deleted from the statistical analysis. The ionic concentration of each of the elements in the lake water analysis (except for the Nashwauk Drift manganese) are considerably less than those of the groundwater concentrations, which suggesting that lake water is diluted groundwater .

Lake Sediment

The analytical results for the lake sediment data are listed in Table 8. The concentrations of cobalt, copper, nickel, and zinc have been recorded in parts per million, with the remaining metals in weight percent. Group range, median, mean, and standard deviation for each element are given in Table 11.

Lake sediment samples have both higher element concentrations, and a wider range of concentrations as compared to the water samples. Lake sediment concentrations are typically in the parts per million range as opposed to the parts per billion range of the water samples. Recognition of suspect mineralization is more easily discerned and more reliable. For these reasons lake sediment is often preferred over water as a geochemical sampling medium for mineral exploration.

Results of the analysis show two anomalous sample sites: Clubhouse Lake and Bear Lake. The concentration of zinc measured in the three Bear Lake samples (#3916, 3917, 3918) is unusually high. Zinc concentrations are 240, 244, and 247 ppm compared to a median value (in Nashwauk Drift samples) of 54 ppm. The Bear Lake cobalt concentrations are also the highest measured, although they are not extreme. Bear Lake is located in Rainy Lobe outwash, with bedrock

<u>TABLE 11 LAKE SEDIMENT STATISTICS</u>

Nashwauk Drift (N=12)

	Range	Mean	Standard Deviation	Median
pHs	7.3-8.4	7.9	0.42	7.9
pHw	6.1-7.0	6.6	0.30	6.6
Depth	7-55	32	29.9	30
Cobalt	7-113	13	4.8	9
Copper	7-21	15	5.6	13
Nickel	12-26	19.8	5.0	16
Zinc	50-247	118.7	78.7	54
Iron	0.59-9.40	4.88	3.87	3.85
Manganese	0.025-0.736	0.265	0.230	0.293
Calcium	0.12-1.32	0.52	0.37	0.89
Potassium	0.32-1.13	0.63	0.25	0.55
Magnesium	0.26-0.73	0.45	0.15	0.37
Sodium	0.14-0.88	0.34	0.22	0.30
LOI	30.82-64.47	42.6	9.6	38.9

Caribou Drift (N=11)

	Range	Mean	Standard Deviation	Median
pHs	7.4-8.6	8.0	0.4	8.0
pHw	6.2-6.9	6.5	0.2	6.6
Depth	9-95	40	29.1	28
Cobalt	4-13	8.1	2.5	8
Copper	8-23	13.4	5.3	12
Nickel	7-24	14.5	5.1	16
Zinc	27-127	56	27.5	53
Iron	0.82-11.30	3.85	3.37	3.7
Manganese	0.035-4.9	1.0	1.70	0.27
Calcium	0.35-2.26	1.0	0.59	0.84
Potassium	0.22-1.53	0.56	0.37	0.52
Magnesium	0.15-0.65	0.39	0.18	0.34
Sodium	0.12-1.48	0.38	0.39	0.29
LOI	10.56-64.17	45.17	15.25	44.9

very near, and exposed directly at the surface. The lake probably lies within a bedrock basin in crystalline igneous rock. The high anomalous concentrations probably reflect the bedrock chemistry, and possibly sulfide mineralization.

Clubhouse Lake samples (#3910, 3911, 3912) have interestingly high manganese concentrations; 4.9, 3.8 and 1.0 ppm compared to a median value of 0.27 ppm and a mean of 1.0 ppm. Clubhouse Lake, located within St. Louis Sublobe till is the second deepest lake sampled; the anomalous manganese concentrations can probably be attributed to redox conditions.

Areal Variation

In the statistical analysis, samples are separated on the basis of drift type, with no distinction made between till and outwash. The concentration of each of the metals was plotted on a map containing sample location and drift boundaries to detect distribution patterns in the variables (Appendix A). This was done to more clearly portray the relationships between sample location and concentration variation.

The concentrations of sodium, nickel and cobalt show a definite increase towards the till of the Nashwauk Drift. These patterns show up especially well on lake and well samples for sodium; on well samples (only) for nickel; and lake sediment samples (only) for cobalt.

The concentrations of copper, magnesium, calcium and manganese show enrichment towards the Caribou till, the differences especially pronounced in well data for copper, magnesium, and manganese, and well and lake samples for the calcium concentrations.

Zinc has an interesting distribution pattern. The highest concentrations of zinc (127ppm) occurs in the outwash of both drift types. This probably results from the high mobility of this metal in the surficial environment (Table 4). Zinc is the only metal concentrated in outwash rather than the till.

No regional distribution patterns were detected for the metals potassium, iron, or copper. Several high anomalous concentrations have been plotted which adversely influence the group means, although no real patterning could be detected.

STATISTICS

Introduction

The UMD computer center cyber 171 computer was used for the statistical analysis. Two systems of computer programs were used in the analysis, SPSS: Statistical Packages for the Social Sciences (Nie and others, 1975), and BMDP: Biomedical Data Processing (Dixon and Brown, 1979). The research was made possible by a grant from the University of Minnesota Computer Center.

A statistical analysis of the thirteen geochemical parameters was conducted to aid in the interpretation of the chemical differences in drift type. Several different techniques including multivariate statistics were used throughout this study. Multivariate statistics is the analysis of data consisting of more than one variable measured on each observational unit. In this investigation, this involved the analysis of 14 variables (specific conductivity, loss-on-ignition (L.O.I.) depth, pH, Co, Cu, Ni, Zn, Fe, Mn, Ca, Mg, K, and Na) measured on each case. Multivariate methods allow for the consideration of changes in the variables, simultaneously, and in so doing, more closely approximates the natural environment.

Three mathematical assumptions inherent to most statistical problems are that:

1) the sampling is "random"
2) the frequency distribution is normal, and
3) the sample size is sufficiently large to represent the population.

In any statistical study, the population is the object of primary interest. From the population, generalizations, predictions and decisions are made affecting any interpretation. Samples taken from a population are of interest only to the extent that they give insight into the attributes of a population. This, however, does not imply that the samples must be chosen "at random." The lakes and wells for this study were chosen on the basis of availability and accessability, across a traverse of the two drift types. The decision to sample on this basis controls the framework of the statistical problem, which in turn defines the scope of of the study. Statistical inferences that result from the analysis are valid only for the limited situation defined. Deliberate selection of a specific situation (as is the case with this problem) in which the phenomena of interest are purposely displayed may serve as a basis for extending these inferences to other situations on the basis of geological reasoning (Krumbein and Graybill, 1965).

The other mathematical assumption inherent to statistical analysis pertains to the observation that the data in the population(s) are normally distributed, normal in the sense that the variation in the variables (or changes in the concentrations of the metals) can be described by a symmetrically skewed frequency distribution. A normal frequency distribution, which is most often portrayed graphically by a bell-shaped curve, serves as the basis for the statistical tests.

Studies of the frequency distribution of elements in natural materials however, (Tennant and White, 1959; Ahrens, 1957; and Miller and Goldberg, 1955) suggest that the distributions are log-normal, with useful results from a statistical analysis obtained only by assumming log-normal behavior. Within the realm of multivariate statistics, there were two options available realizing this circumstance:

1) to manipulate the data so it behaves as if it were normally distributed and use the normal probably distribution as a basis for the statistical tests, or

2) to analyze the data using non-parametric statistics: techniques which do not use the assumption of normality or linearity in the data.

Due to the lack of a wide range of non-parametric multivariate techniques, as well as their acceptance as a statistically valid tool, it was decided to employ manipulation of the data (1).

Preliminary inspection of the raw data, and log plots of the concentrations of the elements suggested that the elements were approximately log-normally distributed. Each of the elements were transformed to linearize the departure of the distribution from normality. (Krumbein and Graybill, 1965). Transformation is a process which mathematically alters each variable. This is a particularily useful technique for standardizing data that are distributed in such a manner that the logarithms of the newly derived values result in a normal frequency distribution (Aubrey, 1954 and 1955). The log-transformation (base 10) using Zinc as an example is: Zn = LOG (Zn + 0.005). Multiplying the concentration of each metal by 0.005 eliminated the possibility of entering the log of zero (a non-real number) into a computation. Each of the ten metals were transformed, so as to change the value of their concentration, not their relative significance. Specific conductivity, pH, depth and L.O.I., more closely approximate normal distribution, and therefore were not transformed.

Correlation Analysis

A correlation analysis of the variables was used to identify various relationships and characteristics that may aid in the interpretation of the geochemical results. Product-moment correlation coefficient matrices were used to demonstrate the existence (or lack of existence) of interrelationships among the transformed variables. The nature of the relationship or degree of correlation between variables is represented by a correlation coefficient which varies from -1 (an inverse relationship) to +1 (a direct relationship). Correlation matrices were derived for lake, groundwater, and lake sediment samples, and separately for each of the two drift types. In addition to the ten metals, five other parameters were correlated: specific conductivity, depth, sediment and water pH, and loss-on-ignition (L.O.I.).

Correlation Analysis of Well Data

Caribou Drift

Results of the correlation analysis for well data are shown in Table 12. Coefficients greater than 0.46 are significant at the 5% level; and greater than 0.58, at the 1% level. The most striking

TABLE 12 Correlation Matrix for Transformed Well Data
Significance: 5% (0.456), 1% (0.575)

	pH	SPCOND	Cu	Ni	Zn	Fe	Mn	Ca	K	Mg
<u>Nashwauk Drift</u>										
pH	1.0000									
SPCOND	.6498	1.0000								
Cu	-.4239	-.8374	1.0000							
Ni	-.0783	.1459	-.6190	1.0000						
Zn	-.4072	.1113	-.2673	.4083	1.0000					
Fe	-.1946	-.2364	-.2653	.8944	.2233	1.0000				
Mn	-.1391	-.0660	-.4082	.8529	-.0038	.8205	1.0000			
Ca	-.0110	.2138	-.5337	.5039	-.0422	.2824	.7187	1.0000		
K	-.2690	.2376	-.6007	.5595	.6271	.3614	.3140	.4766	1.0000	
Mg	-.0891	.0859	-.4386	.5840	-.0954	.4209	.8485	.9601	.3325	1.0000
Na	.3060	.7774	-.4955	-.1776	-.1099	-.4976	-.1795	.1182	-.0477	.0613
<u>Caribou Drift</u>										
pH	1.0000									
SPCOND	0.1019	1.0000								
Cu	-.6383	-.3397	1.0000							
Ni	.5539	.2221	-.1990	1.0000						
Zn	-.6821	-.2421	.6726	-.2480	1.0000					
Fe	-.2895	-.2529	-.0225	-.2494	.3020	1.0000				
Mn	.1519	.2994	-.4125	.0534	-.2382	.2354	1.0000			
Ca	.2754	.9166	-.4784	.3114	-.4496	-.3790	.3412	1.0000		
K	.4018	.7250	-.5762	.2526	-.5789	-.3099	.5842	.7010	1.0000	
Mg	-.2977	.7410	-.0878	-.0742	-.2668	-.1464	.0998	.7019	.3971	1.0000
Na	.4388	.7369	-.2834	.2420	-.4946	-.2580	.2818	.6378	.7286	.4478

relationships revealed in the analysis are the positive relationships among the "major" elements, i.e. between calcium and magnesium (0.70); calcium and potassium (0.70); and sodium and potassium (0.73). All major element correlations for Caribou Drift samples were significant at the 1% level. A strong positive correlation also exists between each of the major elements and specific conductivity, i.e., calcium (0.92); magnesium (0.74); potassium (0.73); and sodium (0.74).

A high positive correlation exists between zinc and copper (0.67); however, it is the only significant association among the Caribou Drift minor metals. Each of the minor metals, except nickel (0.55), and manganese (0.15) shows a moderate to strong negative relation to pH.

<u>Nashwauk Drift</u>

A strong positive correlation exists between calcium and magnesium (0.96), and between calcium and potassium (0.48). Each of the other major element correlations are near zero, indicating no correlation. Sodium has a high positive correlation with specific conductivity, but this is the only significant association between SPCOND and any of the major elements. The pH has a significant positive correlation only with SPCOND (0.65). A negative correlation exists between pH and every other variable.

Several strong positive correlations exist among the Nashwauk Drift's minor metals: between iron and nickel (0.89), manganese and nickel (0.85), iron and manganese (0.85). Copper has a low negative correlation to each of the other minor metals except nickel (0.62).

Dicussion

Results of the correlation analysis for well data show, especially for the calcareous Caribou Drift, a strong overall association among the major metals. Calcium and magnesium carbonates are abundant in the Caribou Drift, and can easily be leached from the drift and incorporated into the ground- and surface waters, resulting in positive calcium and magnesium correlations. The relationships observed in the correlation analysis are, therefore, not suprising. Work by Bright (1968), Dean and Gorham (1976), and Cotter and others, (1965) state that the groundwaters in the region contain principally calcium, magnesium and bicarbonate. These ions are dominant in the waters, and probably control the conductivity, hence the strong correlation with conductivity. The pH seems to follow generally the same pattern, but lacks the sensitivity of the conductivity.

The minor metal associations in the analysis show a different trend. The strongest positive correlations are observed in the Nashwauk Drift samples. The Nashwauk Drift correlation matrix reveals generally high correlations among iron and manganese, and between these metals and nickel. High concentrations of iron and manganese are characteristic of the groundwaters in this area (Cotter and others, 1965). Iron and manganese are metals most affected by oxidation-reduction; their levels in the groundwater are determined by the relative rates of the introduction of oxygen by primarily organic matter, but also sulfides, ferrous silicates, or carbonates. The most important variables are: 1) the oxygen content of the recharge area, 2) the distribution and reactivity of the organic material present, 3) the distribution of potential redox buffers in the aquifer (primarily iron and manganese oxides) and 4) the circulation rate of the groundwater [the shorter the residence time, the lower the result-ing oxidation potential, (Drever, 1982)]. One would expect that in deeper wells (with depth generally associated with more reducing conditions) that higher concentrations of especially iron and manganese would exist. In fact, higher concentrations of iron and manganese are found in Nashwauk Drift samples, yet the wells of the Caribou Drift are, on the average, deeper. This relationship suggests that oxidation and reduction may not be the dominant control on these metals. The relations that do exist between the minor metals may indicate a common bedrock geologic association, which seems to be more pronounced in the Nashwauk Drift.

Correlation Analysis of Lake Data

Caribou Drift

Results of the correlation analysis for the lake data are given in Table 13. Coefficients greater than 0.55 are significant at the 5% level, and coefficients greater than 0.68, at the 1% level. The strongest correlations occur between SPCOND and the major elements: calcium (0.91), potassium (0.72), magnesium (0.66), and sodium (0.59); and also between SPCOND and nickel (0.92). A strong positive correlation occurs between calcium and potassium (0.92), although there is little correlation among any of the other major elements.

Significant positive correlations exist among the minor metals, especially iron, zinc and copper [i.e. iron and zinc (0.98) and zinc

TABLE 13 Correlation Matrix for Transformed Lake Data
Significance: 5% (0.553), 1% (0.684)

	pH	Sp. Cond.	Cu	Ni	Zn	Fe	Mn	Ca	K	Mg
<u>Nashwauk Drift</u>										
pH	1.0000									
Sp. Cond.	0.4020	1.0000								
Cu	0.3196	0.7096	1.0000							
Ni	-.4783	0.5766	-.3951	1.0000						
Zn	0.2561	-.3675	0.8302	-.5619	1.0000					
Fe	-.3051	0.6999	-.9971	0.3492	-.8031	1.0000				
Mn	-.3199	0.8061	-.2330	-.2013	0.2339	0.2343	1.0000			
Ca	-.4645	0.9041	0.9188	0.6493	-.7241	0.9045	0.4834	1.0000		
K	-.2445	0.5050	-.9288	0.4011	-.9353	0.9063	0.0129	0.7992	1.0000	
Mg	0.0302	-.1625	-.2181	0.2166	-.5787	0.1591	-.4258	0.0994	0.5594	1.0000
Na	-.3876	0.7232	-.9662	0.6080	-.9010	0.9485	0.1932	0.9481	0.9335	0.3122
<u>Caribou Drift</u>										
pH	1.0000									
Sp. Cond.	-.2938	1.0000								
Cu	-.0619	0.4063	1.0000							
Ni	-.2853	0.9152	0.0402	1.0000						
Zn	0.0840	-.1898	0.6431	-.5623	1.0000					
Fe	0.1328	-.3807	0.4753	-.7066	0.9764	1.0000				
Mn	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
Ca	-.2514	0.9069	0.7001	0.6608	0.2392	0.0368	0.0000	1.0000		
K	-.2104	0.7244	0.6359	0.4259	0.4962	0.3388	0.0000	0.9166	1.0000	
Mg	-.1649	0.6627	0.3060	0.7229	-.5318	-.6854	0.0000	0.4556	0.0620	1.0000
Na	-.2317	0.5942	-.4586	0.7789	-.5731	-.6034	0.0000	0.3133	0.2861	0.1797

and coper (0.64)]. Nickel shows high positive correlations with the major elements, and negative correlations with the minor metals. The concentrations of manganese for each of the Caribou lakes sampled remained constant; no coefficients were calculated in the analysis.

Nashwauk Drift

High positive correlations occur between SPCOND and the minor metals: with calcium (0.90), and sodium (0.72); and between calcium and potassium (.0.80), calcium and sodium (0.95), and sodium and potassium (0.93). Little correlation occurs between calcium and magnesium (0.23).

Several significant associations occur among the minor metals. Zinc and copper are highly correlated (0.83), but show high negative correlations to each of the other variables. Nickel has a significant positive correlation only with calcium (0.65), and sodium (0.62), and a significant negative correlation with zinc. Very strong positive correlations occur among iron and the major elements: with calcium (0.90), potassium (0.91), and sodium (0.95); and also between SPCOND and iron (0.70). A strong association also occurs between SPCOND and manganese (0.81), with little correlation between iron and manganese (0.23).

Discussion

High positive correlations exist among several of the major element contents in the Caribou Drift analysis. These relations are the same, and in some cases stronger among the major element contents of the Nashwauk Drift. The lack of significant associations among the majors with calcium (particularly among the calcareous Caribou samples), as well as the depletion in the lake concentrations of calcium in general, probably result from the precipitation of $CaCO_3$ in the lake environment. A rise in both the water temperature and pH of lakes in late summer months results in a decreased solubility of $CaCO_3$, with subsequent precipitation (Brugam, 1981).

Strong positive correlations exist among SPCOND and the major element content in the Caribou Drift samples as compared to the Nashwauk samples, whose correlations are on the average weaker, yet still significant.

Several strong positive associations exist among the minor metals in the lake water analysis. These relations appear to be strongly influenced by the iron content of the Caribou Drift samples, and iron and manganese of the Nashwauk Drift samples. Adsorption by hydrous oxides of iron and manganese is probably the most important control on the concentrations of metals in the surficial environment (Coker and others, 1979; Gorham and Swaine, 1965; Jenne, 1968; and Levinson, 1974). Scavenging occurs through one of two processes, adsorption and coprecipitation. Adsorption occurs when a dissolved ion or molecule becomes attached to the surface of a pre-existing solid, and coprecipitation, when a dissolved species is incorporated as a minor component in a solid phase as that phase itself is precipitated (Drever, 1982).

Lake water appears to be less sensitive than groundwater to differences in drift type. This conclusion may be a result of the smaller sample size (n=12 for lakes as compared to 16 for wells), or possibly due to the real differences in the ionic concentrations. Groundwaters, being in direct contact with the glacial sediments, should contain higher ionic concentrations. Lake waters, in comparison, are groundwaters diluted by atmospheric input and surface runoff. The concentration differences do not directly affect the correlation analysis; however, the relative ionic concentrations might in effect "dilute" the sensitivity of the lake water to differences in drift type.

Correlation Analysis for Lake Sediment Data

<u>Caribou Drift</u>

Results of the correlation analysis for lake sediment data are presented on Table 14. Correlation coefficients in the lake sediment analysis greater than 0.41 are significant at the 5% level, and greater than 0.53, at the 1% level. High positive relations occur among several of the minor metals: i.e. cobalt and nickel (0.71); copper and zinc (0.76); nickel and copper (0.65); and manganese and cobalt (0.45). Iron is negatively correlated with depth (-0.51), and shows little correlation to the other variables. Significant negative correlations occur between depth and most of the metals: copper (-0.61), zinc (-0.64), and iron (-0.51). Manganese and cobalt show positive correlations to depth, 0.68 and 0.31, respectively.

A significant positive correlation exists between the pH of water and the pH of the lake sediment (0.56). The pH of the sediment shows

TABLE 14 Correlation Matrix for Transformed Lake Sediment Data
Significance: 5% (0.413), 1% (0.526)

	pHW	pHS	DEPTH	Co	Cu	Ni	Zn	Fe	Mn	Ca	K	Mg	Na
Nashwauk Drift Correlation													
pHW	1.0000												
pHS	0.9479	1.0000											
DEPTH	0.2077	-.1612	1.0000										
Co	0.5342	0.6588	-.6702	1.0000									
Cu	-.3184	-.2686	0.9514	-.6080	1.0000								
Ni	0.3732	0.5337	-.4309	0.9144	-.2785	1.0000							
Zn	0.5527	0.6702	-.7047	0.9935	-.6711	0.8652	1.0000						
Fe	0.6217	0.5557	-.4468	0.6901	-.3045	0.7213	0.6530	1.0000					
Mn	0.3518	0.4687	-.6573	0.9561	-.5132	0.9566	0.9286	0.7491	1.0000				
Ca	-.7980	-.9130	0.4023	-.8223	0.5119	-.6313	-.8541	-.4742	-.6353	1.0000			
K	0.2680	0.4495	0.5335	0.2506	0.6020	0.5242	0.1800	0.2943	-.2734	-.2967	1.0000		
Mg	-.4702	-.3164	0.4406	-.0405	0.6691	0.3541	-.1363	0.0657	0.1763	0.3572	0.6569	1.0000	
Na	-.5045	-.4326	0.3390	-.1135	0.6090	0.2812	-.2166	0.1416	0.1395	0.5154	0.4845	0.9506	1.0000
LOI	0.1073	-.0092	0.3875	-.6347	0.1180	-.8381	-.5602	-.5975	-.8221	0.1222	-.3517	-.6338	-.6590
Caribou Drift Correlation													
PHW	1.0000												
PHS	0.5558	1.0000											
DEPTH	0.5003	0.7171	1.0000										
Co	0.3071	0.6020	0.3049	1.0000									
Cu	-.7079	-.2893	-.6059	0.1757	1.0000								
Ni	-.1347	0.2289	-.1069	0.7113	0.6466	1.0000							
Zn	-.4137	-.2225	-.6426	0.2207	0.7645	0.5092	1.0000						
Fe	0.2199	-.1730	-.5124	0.2322	0.1812	0.1055	0.2914	1.0000					
Mn	0.5138	0.4428	0.6873	0.4481	-.5864	-.1642	-.5958	-.0282	1.0000				
Ca	0.0879	0.1189	0.3411	-.2312	-.4044	-.4088	-.3946	-.4439	0.3585	1.0000			
K	-.5326	-.2703	-.5005	-.5028	0.4474	0.0040	0.4302	-.1350	-.8373	-.3075	1.0000		
Mg	-.5062	0.1757	-.1363	0.2427	0.7133	0.7006	0.4562	-.2875	-.4864	-.2119	0.4829	1.0000	
Na	-.5881	-.3034	-.4396	-.6124	0.4199	-.1174	0.3261	-.2480	-.7732	-.1230	0.9445	0.4111	1.0000
LOI	-.4987	-.6038	-.7342	0.0077	0.5429	0.2493	0.3910	0.3804	-.2916	-.1618	0.0524	0.1732	0.0145

a high positive correlation with depth (0.72), cobalt (0.60), and also manganese (0.44).

Moderately high positive correlations occur between L.O.I. and several of the metals: with copper (0.54), nickel (0.25), zinc (0.39), and iron (0.38); L.O.I. is negatively correlated with each of the other variables.

No strong correlations among calcium, potassium, magnesium, and sodium were found. Calcium has a low negative correlation with each of the major metals. Significant positive correlations occur between magnesium and potassium (0.48), and potassium and sodium (0.94); magnesium has a high positive correlations with copper (0.71), nickel (0.70), and zinc (0.46).

Nashwauk Drift

High positive correlations occur among the minor metals: cobalt, nickel, zinc, iron, and manganese. Cobalt has an almost perfect correlation with zinc (0.99), and very high positive correlations with manganese (0.96), nickel (0.91), and iron (0.69). Manganese, too, has very high positive relations with nickel (0.96), zinc (0.93), and iron (0.75). Each of the other minor metals shows very high positive correlations except copper. Copper exhibits a significant negative correlation to cobalt (-0.60), zinc (-0.67) and manganese (-0.51), and high positive correlations to each of the major elements, and to depth (0.95). Depth shows a negative correlation to each of the other minor metals, and low positive (insignificant) correlations to the major elements.

Sediment pH and water pH are highly correlated (0.95); and each have significant positive correlations to the minor metal contents with negative, generally low correlations to the major metal contents and also to copper.

Moderately high positive relations occur among few of the major elements: calcium and sodium (0.51); sodium and magnesium (0.95); potassium and magnesium (0.66); and potassium and sodium (0.48).

Discussion

The strongest correlations in the lake sediment analysis occur among the minor metal contents. Results of the Nashwauk Drift analysis show a strong positive correlation between iron and manganese, with very strong positive correlations to each of the other minor metals. Copper is an exception, showing negative correlations to the minor metals, and a high positive association to depth. The reasons for this association are unclear. Little correlation occurs between copper and either L.O.I. or pH, factors which might serve to explain the association of copper to depth.

Control of the minor metals in the lake sediment environment is thought to be a result of redox and perhaps organic complexing. Iron and manganese brought into a lake environment will be oxidized, and subsequently precipitated. The precipitation may include other minor metals, through adsorption or coprecipitation. At the sediment-water interface, the lake floor is characterized by a zone of oxidized sediment, overlying the highly reducing organic material gyttja. In this reducing environment, chemical dissolution occurs, via 1) the organic complexation, or 2) reduction, with subsequent release into overlying waters (Coker and others, 1979).

Loss-on-ignition shows a low positive correlation with copper (0.54), and relatively high significant correlations with zinc, nickel and iron in the Caribou analysis. These associations suggest that those minor metals may be accumulating in the more organic-rich lake sediment. The organics, which make up an average of 40% of the gyttja, behave as negatively charged species which can be neutralized by the adsorption of metal ions. Coker and others (1979); Gorham and Swaine, (1965); Levinson, (1974); and Rose and others, (1979) suggest that scavenging of metals by organic material is the principal mechanism affecting the distribution of metals in the lake environment.

Factor Analysis

In a further attempt to simplify the interrelationships among the variables, a multivariate technique called factor analysis was employed. Factor analysis as applied to geochemistry can be appreciated when it is considered that the distribution of each element in any naturally occurring material is determined by a number of different geological processes, where each process diversely affects each variable (Cameron, 1967). Factor analysis simplifies the complex nature of the geochemical components by considering the effects of the distribution of the variables rather than their distributions alone. The effects can be understood in terms of geological processes, in this case processes operating in the surficial environment: hydrolysis, oxidation-reduction, dissociation, etc.

The data were reduced to two significant factors, in each of the three attempts (lake, well and lake sediment). The two factors correspond to a division between the major and minor constitutents of the samples, much the same as are the results of the correlation analysis. Geologically, this separation may be important, although not in terms of discerning chemical differences in the variables, or predicting what (or to what degree) chemical processes are occurring. The only exception was in the variable zinc. In the well analysis, zinc almost exclusively loaded on a third factor. This factor accounted for 8% of the variabiliity in the data. Because this metal is concentrated in outwash samples rather than in till, it is believed that the metal is not reflecting the chemistry of the drift. Its significance here probably represents a bedrock (sulfide?) association.

The t-test

The t-test is a simple statistical test used to determine whether or not a statistical difference exists between the variables of two groups, in this case the two drift types. Group log means serve as the basis for the comparison. The goal of the analysis is to determine whether or not a difference between two samples is significant in that the differences reflect a true difference between two populations rather than the natural variability expected between any two samples within a population.

Several of the variables showed a significant separation between the drift types. Significance was determined at the 95% level of confidence. The variables that showed significant separation, and the drift type with which their concentrations are highest are presented in Table 15.

Table 15 Significant Results of the t-test
Elements which show significant separation between groups and drift type in which each element is enriched.

	Nashwauk Drift	Caribou Drift
Wells	Na	pH, Mn, Ca, Mg
Lakes	Fe, Mn, Mg	-----
Lake Sediment	Co, Ni, Zn, K, Na	pH_{water}, Ca, Mn

In the analysis of the lake data, only three variables: iron, manganese and magnesium showed a significant separation, all of which showed enrichment in the Nashwauk Drift. Results of the well data disclose the variables pH, manganese, calcium and magnesium, all with higher concentrations in the Caribou Drift. The lake sediment data closely resemble the results of the well analysis, with pH, manganese, and calcium enriched in the Caribou Drift, and cobalt, nickel, zinc, potassium and sodium enriched in the Nashwauk Drift.

Discussion

Several of the variables show a significant separation between the drift types. Especially important are the group differences observed in well and lake sediment data for pH, calcium and (less significantly) magnesium, all of which show enrichment in the Caribou Drift. This relationship (and association) can be explained in terms of the high carbonate content of the Caribou drift, which results not only in higher concentrations of calcium and magnesium, but also an increased pH.

An interesting relationship in the manganese concentration was revealed in the analysis; the manganese concentrations show a significant separation in all media, although concentrated in Nashwauk Drift for lake samples and Caribou Drift for well and lake sediment samples. Manganese, iron, and less significantly, zinc, are metals which are most strongly affected by oxidation-reduction reactions (Dean and Gorham, 1976). Because they are more mobile under reducing conditions, increased concentrations of manganese, iron and zinc should be strongly associated with depth. On the average, the depth of the Caribou Drift wells and lakes exceed Nashwauk Drift wells and lakes. The enrichment of iron and manganese in Nashwauk Drift relative to that of Caribou Drift cannot be explained on the basis of oxidation-reduction.

Sodium concentrations for both well and lake sediment data show significant separation, in both cases enriched in Nashwauk Drift. This difference is thought to involve the bedrock chemistry. Results of the lake sediment t-test also show significant separation for Co, Ni, Zn, and K, all with higher concentrations in Nashwauk Drift.

Several group differences have become apparent as a result of the t-test. These differences seem especially significant when the results of one sampling medium corroborate those of another. This association can be seen among several of the variables with well and lake sediment data.

Multivariate Procedures

Introduction

There are two multivariate procedures used widely in geology: classification and discrimination. The object of both is to separate out homogeneous and distinct groups on the basis of, in this study, their geochemical components. By considering changes in several of the variables simultaneously, the relations among variables can be better understood. Both procedures are related; yet there are distinct differences.

Discrimination analysis involves an *a priori* knowledge of the relations between the samples (Davis, 1973). In discriminant analysis, the samples are divided into two groups which correspond to the two drift types. The aim of the analysis is to produce the most significant separation of the variables on the basis of this predetermined knowledge. The result is a linear combination of the geochemical data which produces the maximum difference between the groups.

In contrast, a classification type analysis is one which is internally based; prior to the analysis there is no predetermined knowledge of the relations between the samples. The object of a classification-type analysis is to separate the samples into groups (or clusters) on the basis of their measured variables.

Cluster Analysis

Cluster analysis is a data reduction and reorganization technique which provides a statistical treatment of large quantities of numerical data. The procedure is accomplished through a pair-by-pair comparison of either cases (Q-mode cluster analysis) or variables (R-mode cluster analysis). In this study Q-mode cluster analysis (clustering of cases) was used in an attempt to delineate some geographical distinction between cases based on the similarities and/or differences in the variables.

In the analysis, the raw data matrix is first normalized in order to give equal weight to each of the variables. Using the product-moment correlation coefficient, a similarity matrix is calculated between all possible pairs of samples. This matrix is systematically searched for the highest similarity coefficient, which is then deleted from the matrix. The procedure is continued until all samples at lower levels of association are paired. Clustering of cases based on their means begins with all samples in one cluster. At each successive step one cluster is split into two with each case reallocated into the cluster whose center is closest. Results of cluster analysis for each of well, lake and lake sediment data are displayed in dendrograms, which represent the end product of the clustering procedure on a two dimensional heirarchical diagram.

Cluster Analysis of Well Data

Results of the clustering for transformed well data are displayed in the dendrogram in Figure 18. The dendrogram reveals two distinct groups, which correspond to the two drift types. Only two cases, numbers 15 and 17 were incorrectly classified, but because geographically both are located near the junction of the two drift types, the difference can be attributed to mixing. Even more important in the results of the well clustering is the fact that, as clustering progressed, the cases were further subdivided by drift type. Successive clustering delineated the cases into those collected from till and those collected from outwash.

Cluster Analysis of Lake Data

Results of cluster analysis for transformed lake data are shown on the dendrogram in Figure 19. Again, the two major groups correspond to the two major drift types, with the exception of four cases, as noted with an asterisk. No aerial justification seems to exist for the four cases improperly classified. They appear to be scattered randomly throughout the field area. Further clustering however did not delineate till from outwash as was the case with the well clustering.

Lake Sediment Cluster Analysis

Clustering of the lake sediment data has delineated, on its first attempt, three clusters (Fig. 20). The three clusters correspond to samples collected from Rainy Lobe drift, samples collected from St. Louis Sublobe drift, and samples collected by the DNR (project 71-3, 6/1977) in a reconnaissance geochemical survey of Itasca County. Four of these seven lakes were incorrectly classified according to the drift type in which they are located, the only miss-classified cases in the lake sediment analysis.

Subsequent clustering divided the Rainy Lobe samples into those collected in till from those collected in outwash, although it produced meaningless combinations from the St. Louis Sublobe data.

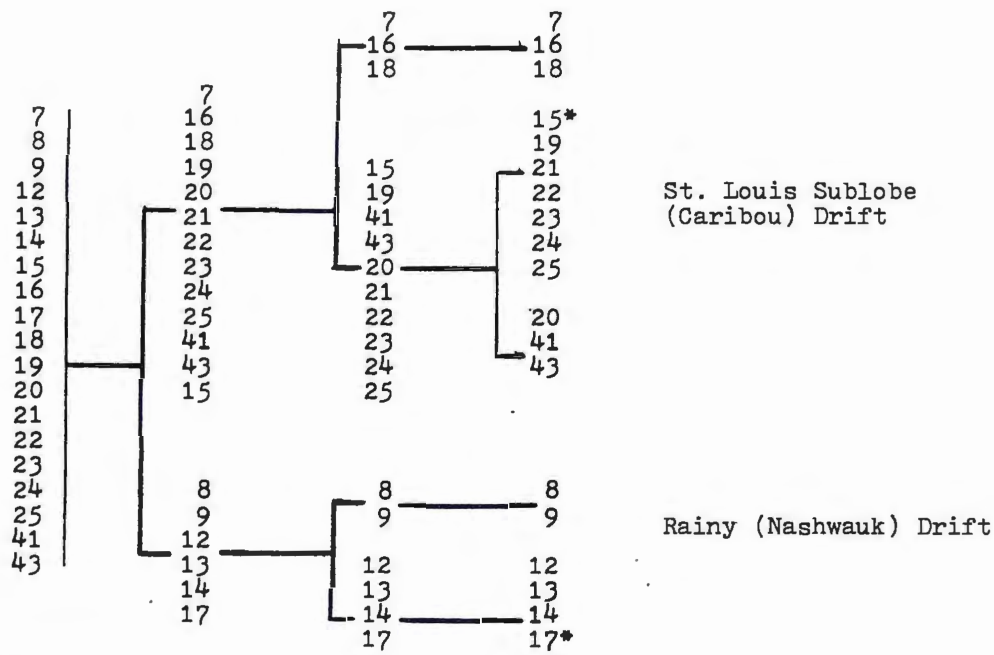


Figure 18. Well Data Clustering Dendrogram.
*indicates cases incorrectly clustered.

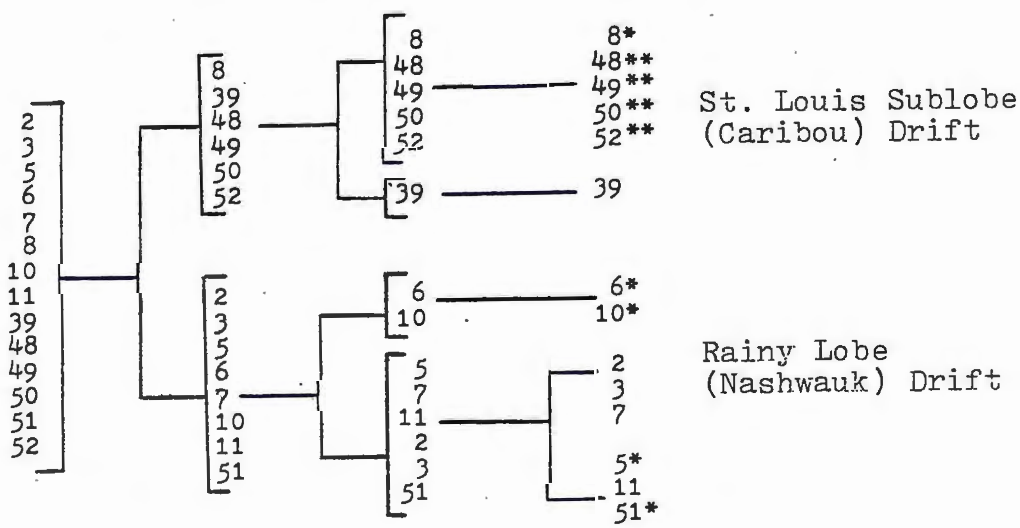


Figure 19. Lake Data Clustering Dendrogram.
* indicates cases incorrectly clustered
** indicates sites sampled by the DNR

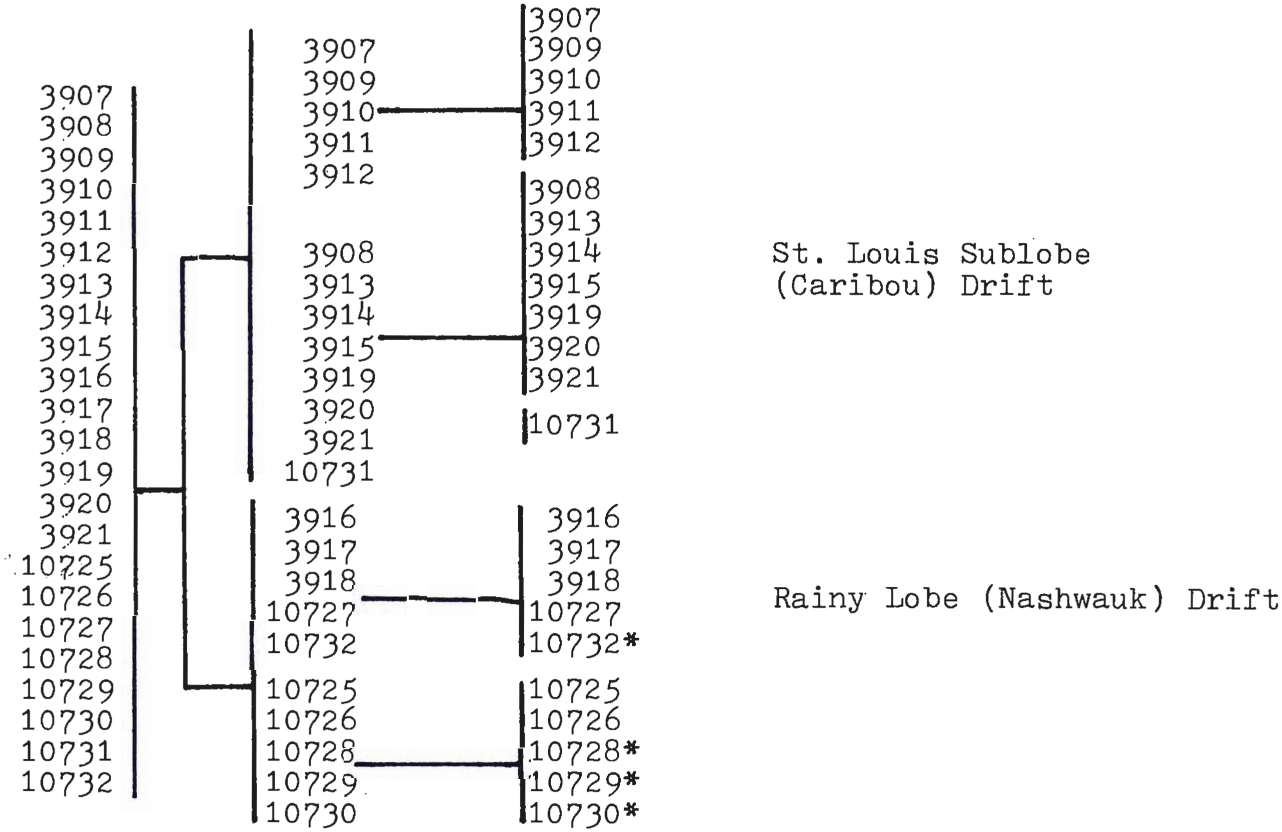


Figure 20. Lake Sediment Clustering Dendrogram.
* indicates sites incorrectly clustered.

Discussion

Successful clustering was accomplished in each of the three sampling media. Clustering was most successful in the well data analysis where, with successive clustering, the cases were subdivided into till and outwash samples within each of the two drift types. The lake data were delineated into two major groups which correspond to the two major drift types, although the degree and rate of success was less significant than were the results of the well analysis. This may suggest (again) that lake water is not as sensitive as groundwater to differences in drift chemistry. Differentiation of lake sediment data was also successfully accomplished by cluster analysis.

Two important conclusions can be drawn from the results of the cluster analysis. The first is that the chemistry of these three systems differ to such a degree that the two drift types can be distinguished by cluster analysis. This in turn implies that the major influence on the chemistry of these systems is the drift lithology. Barr (1978), Bright (1968), Brugam (1981), and Dean and Gorham (1976) have attributed the chemical gradient across the state to such factors as climate (the deficit of evaporation over precipitation), vegetation and/or surficial geology. These conclusions reflect the problem that, when the whole state is considered, gradients in these factors parallel one another (Brugam, 1981). Because of these relations, it is difficult to isolate any single mechanism for the concentration gradient across the state. For the purposes of this investigation however, where the area is relatively small so as to restrict the influences of climate and vegetation, it has been shown that the changes in chemistry can be attributed primarily to the differences in the drift lithology.

Discriminant Analysis

The aims of discriminant analysis are very much the same as those of the univariate t-test: to determine which variables show a statistical difference between drift types. The discriminant analysis however, a multivariate test, takes into account that many of these variables are dependent; their concentrations are influenced by changes in other variables. Calcium, for example, is so closely associated to pH that is has been eliminated from the discriminant function. The concentration differences in calcium can be expressed mathematically in terms of the pH. Calcium, magnesium, and manganese, all of which show up on the t-test with significant separation between drift types, have been eliminated from the discriminant function; they are all dependent variables.

As stated previously, the object of discriminant analysis is to assess the relative importance of the variables that provide the maximum difference between the drift types. The analysis is accomplished by transforming the original set of measurements for each case into a single discriminant score, which in effect collapses the multivariate problem down into one which involves only a single variable. At each step in the analysis, the variable that contributes the most to the separation of the two previouly defined groups is entered into the discriminant function. A test of the significance of the separation of the two groups (the U statistic) is then performed on the variables in the discriminant function.

Results of the discrimination are shown in Table 16, which lists in order of signficance those variables which contribute the most to the separation between the two drift types. Results of the discriminant analysis for well data have shown that pH, iron, and sodium exhibit the largest difference between the drift types. Results for lake data show iron, copper and sodium; and for lake sediment, pH and zinc.

Table 16 Results of Discriminant Analysis The variables that contribute the most to the separation between drift types.

Well Data:	pH, iron and sodium
Lake Data:	Iron, copper, and sodium
Lake Sediment Data:	Zinc and pH

Discussion

Results of the discrimination for the most part corroborate those of previous tests; showing significant differences between drift types for the variables pH, iron, sodium, copper and zinc.

Zinc shows up as the most discriminating variable in the lake sediment analysis. Previously, zinc was reported to be a significant variable: 1) in the t-test, with higher concentrations in the Nashwauk Drift, 2) in the correlation analysis, as strongly correlated with several of the minor metals, and 3) in factor analysis, as the only variable to weigh heavily on one of the factors, representing 8% of the variability in the data. A plot of the concentrations of zinc for well, lake, and lake sediment data (Appendix A) shows that, in all cases, zinc is concentrated in samples collected in outwash as opposed to those collected in till. Zinc is a moderately mobile metal in the surficial environment. The mobility is restricted by its tendency to be adsorbed by either iron and manganese oxides, or insoluble organic matter (Rose and others, 1979). Because concentrations of zinc are higher in outwash than in till samples, the differences observed reflect a source not associated directly with either till type (i.e. bedrock association) or, that the concentration are falsely anomalous due to some geochemical process. Garrett and Hornbrook (1976) attribute anomalous concentrations of zinc in northern Saskatchewan to the amount of organic matter present rather than to its true reflection the chemistry of the drainage basin. The concentration of zinc was found to rise linearly with increasing organic content, as measured by L.O.I. This conclusion is supported by results of the correlation analysis for lake sediment data. A moderately high positive correlation exists between L.O.I. and zinc (0.39), suggesting that organic materials might play a significant role in the control of the concentration of zinc.

Copper appears to be a discriminating variable in the results of the lake data analysis. A plot of the concentrations of copper for each of well, lake and lake sediment data (Appendix A) shows a definite increase in the copper concentrations towards the Nashwauk till for well and lake sediment data, as opposed to an increase towards the Caribou till for the lake data. Copper, like zinc, is a moderately mobile metal (Table 4). Its concentration is also controlled by its adsorption by iron and manganese oxides (Rose and others, 1979). In the correlation analysis, copper shows a moderately high positive association to iron. The differences observed probably result from scavenging in the reducing conditions of the lake environment rather than to actual differences between drift types.

Results of both lake and well discriminant analysis show sodium to be a significant variable. In both cases, it is concentrated in the Nashwauk Drift. Sodium is an unimportant metal in the realm of exploration geochemistry. Its significance in the discriminant analysis and other tests was thought to be a result of the differences in the clay mineralogy between the two drift types. Results of the X-ray analysis, however, show no regional variation in the mineralogy of the clay fraction.

The highest concentration of sodium was observed in a 136 meter well drilled into bedrock. The bedrock (from Sims and others, 1970) consists of biotite and hornblende gneiss and occurs almost exclusively beneath deposits of the Nashwauk Drift. The differences observed in the sodium concentrations probably reflect relative differences in the elemental concentrations between local bedrock types of the report area.

Results of the well and lake sediment analysis show pH to be a discriminating variable. The pH is also a significant variable in the t-test, in all cases, with higher concentrations in the Caribou Drift. Higher values for pH can be attributed to the presence of carbonates in the Caribou Drift, a direct consequence of the chemical difference between drift types.

Statistical Summary and Conclusions

Well water, lake water and lake sediment were chosen in this investigation as the geochemical sampling media. They were chosen under the assumption that they would chemically reflect the glacial or bedrock materials with which they are associated. Results of the cluster analysis clearly demonstrate the fact that they do. Successful separation of drift type was accomplished with all media. The separation was based exclusively on the differences in elemental concentrations. This implies not only that the media reflect the drift types, but, more importantly, that the strongest influence on the chemistry of the two systems is the surficial geology.

The degree of success in their reflecting the chemistry varies with the sampling media. Lake sediment and well water appear to be more sensitive than lake water to chemical differences. The degree of success is based largely on corroboration of results, but also on trends in the raw data. Throughout the analysis, results of the lake sediment and well water closely resemble each other. This holds true for the interrelations among the minor metals in the correlation analysis, the t-test in general, and the degree of separation in the cluster analysis. The ʹrawʹ lake sediment and well water data show consistency, and more distinctive geographical trends.

The reason for the diminished success of the lake water appears to be related to the differences in the ionic concentrations between sampling media. Lake water is groundwater diluted by atmospheric input and surface runoff. An effective geochemical sampling medium must have contact with the materials for which it is trying to portray. Groundwater and lake sediment are at all times in intimate contact with the surrounding sediment. Residence time may also play an important role.

Cluster analysis determined that significant group differences do exist. Given that, the t-test and discrimination analysis were employed to determine what the differences were. A summary of the statistical and chemical results are presented in Table 17.

Many of the relationships can be explained. The enrichment of calcium and magnesium, and the high pH in the Caribou Drift is attributable to the existence of carbonates in the till. The iron and manganese distributions probably are controlled by oxidation and reduction, although no Eh data were obtained in this study to verify this. The occurrences of nickel, cobalt and copper are closely associated with high concentrations of iron and manganese and probably are scavenged by the oxides of those metals. Several interesting observations resulted from this study, including the high concentrations of zinc, which were not directly related to the glacial deposits, and also anomalous sodium, most likely a bedrock association. The zinc can probably be attributed to organic complexing, a product of the metal's high mobility in the surficial environment. Sodium concentrations are quite high in the Nashwauk Drift, and probably relate to the local bedrock chemistry. Finally, some of the data are left unexplained; no supporting evidence could be found to attribute their significance to a 'control' other than an inherent difference between the drift types, which eventually implies bedrock.

Table 17. Summary of Chemical and Statistical Results

	WELLS		LAKES		LAKE SEDIMENT	
	Caribou	Nashwauk	Caribou	Nashwauk	Caribou	Nashwauk
t-test	pH, Mn Ca, Mg	Na	---	Fe,Mn,Mg	pH,Ca,	Fe,Mn
Discrim. Analysis	pH,Fe,Na		Fe,Cu,Na,Mn		pH,Zn	
Factor Analysis	minors/majors Zn		minors/majors Cu, Ni,Fe,Mn Depth		minors/majors	
Cluster Analysis	Separation of Drift types; till and outwash separated 2 cases incorrectly clustered		Separation of Drift Drift types; 4 miss-clustered cases		Separation of Drift types; DNR case incorrectly clustered	

DISCUSSION

The effectiveness of a geochemical survey is dependent on two conditions: 1) that the sampling media come in contact with, and remain in contact long enough for the solution of detectible amounts of the mineral (or indicator), and 2) dispersion patterns must be present and recognizable in the system in order to trace the mineralization back to its source. These patterns may take the form of trains or halos (Boyle, 1971). These criteria can be met under the 'right' physical and chemical setting. The purpose of this thesis is to compare and contrast the physical and chemical nature of two different drift deposits in an attempt to predict and evaluate their use in exploration geochemistry, especially deposits of the St. Louis Sublobe, where exploration geochemistry has met limited success. Rainy Lobe deposits were used as a control; their success has been proven in previous surveys.

The importance of the chemical nature of the drift is in its ability to mobilize and transport metal ions. Eh and pH are the most important factors governing the solubility of elements in the surficial environment. Oxidizing conditions are favorable for the migration of most metals in the surficial environment, which, under reducing conditions would tend to form precipitates. Non-oxidizing systems, characterized by slow-moving, stagnant waters act as sinks and filters in which most of the metal ions are effectively removed, primarily by adsorption and coprecipitation. This process is an advantage in lake sediment geochemistry, but is a deterrent for hydrogeochemical methods.

Probably the most important control on the mobility of metals in the surficial environment is the pH. Most metals are highly soluble in acidic conditions, and tend to precipitate out as oxides or hydroxides as the pH increases (Table 4). The pH is affected by the high carbonate content of the St. Louis Sublobe drift (Caribou Drift) acting to inhibit metal ion migration.

It has been shown in the previous sections, however, that well water, lake water, and lake sediment reflect the chemistry of the drift from which they were sampled. This implies that ions are being transported within these systems, which suggests favorable chemical conditions for the migration of metal ions. The inhibiting factor in the success of exploration geochemistry, at least within the study area, is thought to be the physical rather than the chemical nature of the drift.

Factors of interest concerning the physical nature of the drift are dominantly the texture, the thickness, and the stratigraphic position. In areas covered by either fine textured materials (i.e. silty St. Louis Sublobe till, or lake clays) or thick drift deposits, the mineral deposits can be effectively isolated from circulating, oxidizing groundwaters. The stratigraphic position of the till is of interest to mechanical dispersion. An advancing glacier may incorporate local bedrock into its drift, which can be mechanically dispersed in a down-ice direction. Dispersion patterns may be present as increasing concentrations of elements up-ice: a train. If mineralization were apparent at the surface, mechanical dispersion might enable its detection. Mechanical dispersion is restricted to a glacier that is actively quarrying local bedrock, and depositing a subglacial till.

Deposits of the Rainy Lobe in the area, dominantly a till facies of the Nashwauk Drift consist of a thin layer of a fine-textured, non-calcareous basal till. The abundance of granitic and metamorphic rocks suggest a local origin. Except for its finer-than-average texture, the physical and chemical nature of the drift is favorable for successful geochemical exploration. The detection of anomalously high concentrations of sodium does suggest that the drift is reflecting the chemistry of the bedrock.

The Caribou Drift consists of a thick supraglacial accumulation of calcareous sand and gravel. Caribou till is silty, although is extent is severly limited. Despite the fact that the chemical system was shown to be conducive to the transport of metal ions, all conditions, both physical and chemical seem to be unfavorable for its use as a geochemical sampling media.

The majority of the sediments comprising the drift of the St. Louis Sublobe are permeable sands and gravels, although their extreme thicknesses are thought to act as an effective barrier to circulating groundwaters. To compound its uselessness, the St. Louis Sublobe appears to have overridden pre-existing glacial deposits (the Wadena Lobe in the west and the Rainy Lobe in the east). Even without its great thickness, the Caribou Drift would still probably not reflect the chemistry of the underlying bedrock.

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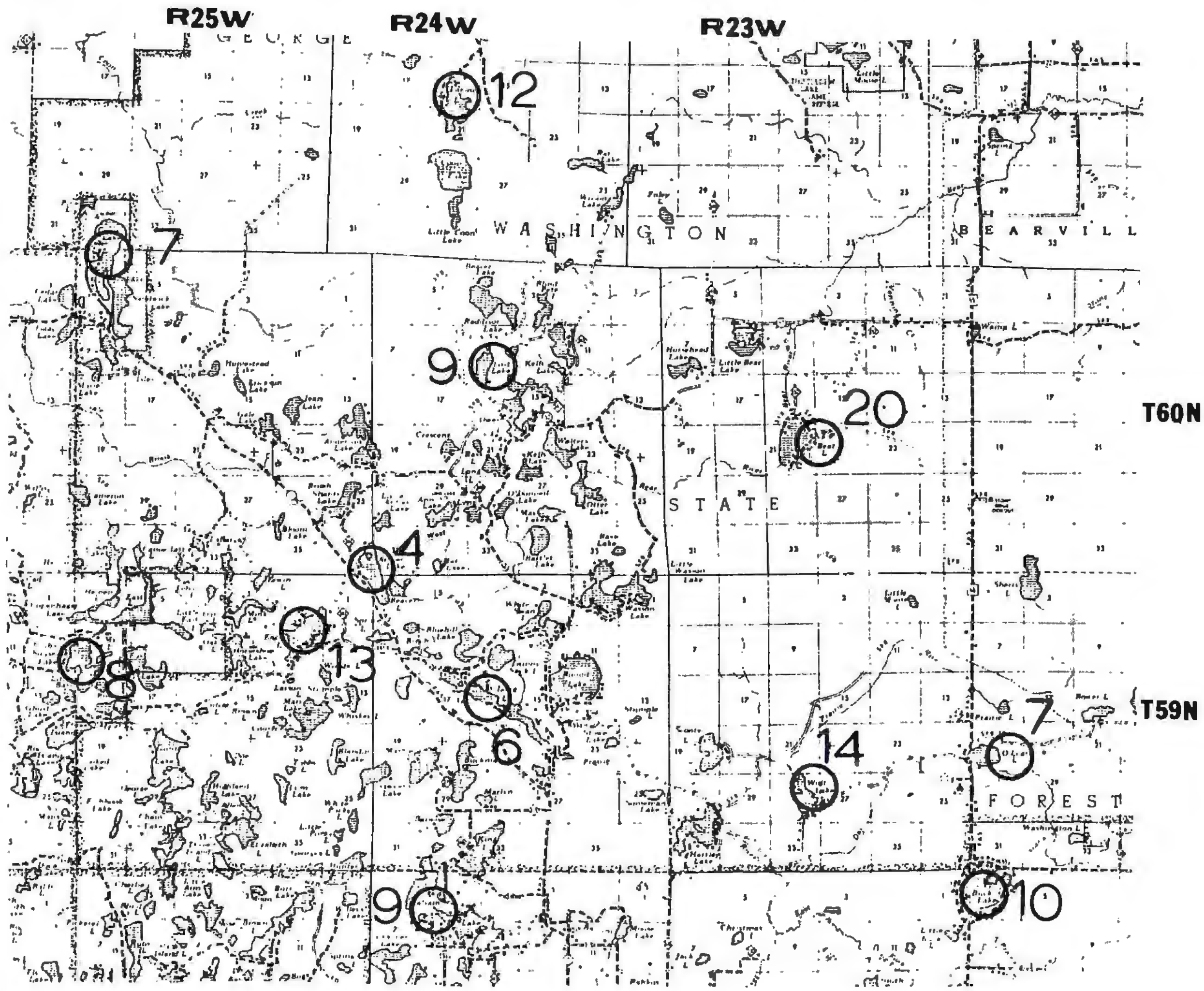
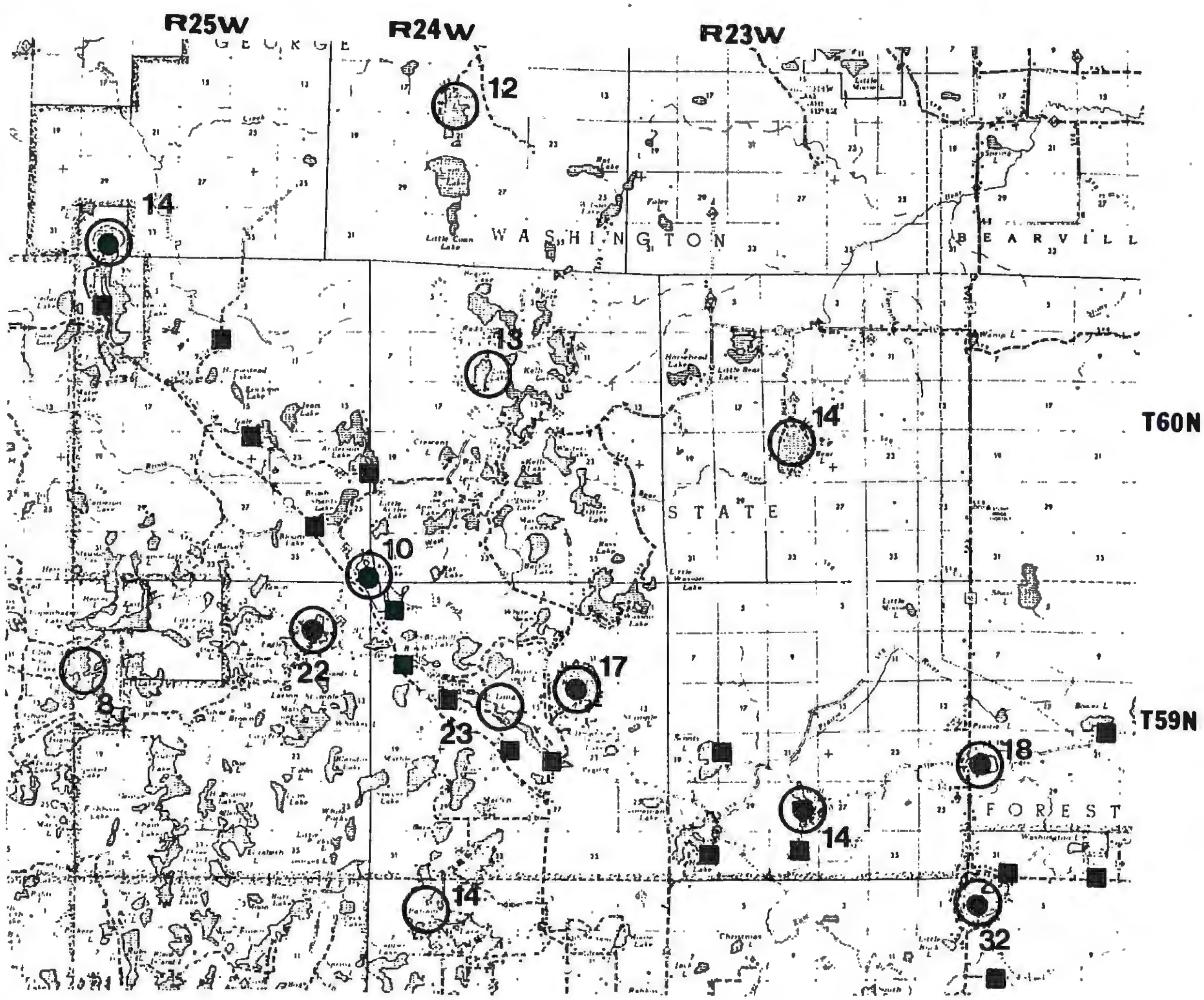
APPENDIX A

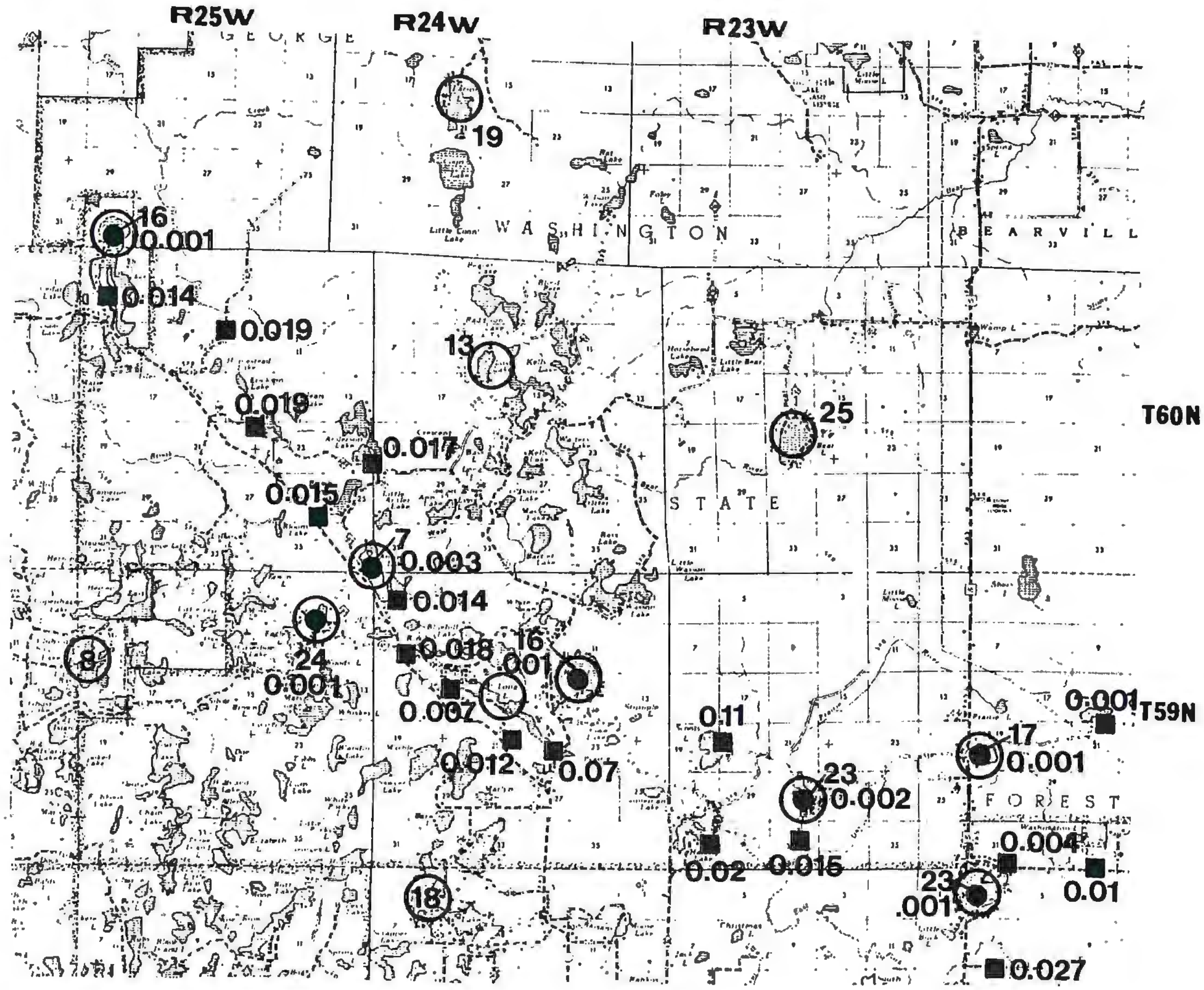
Sample location vs. concentration variation



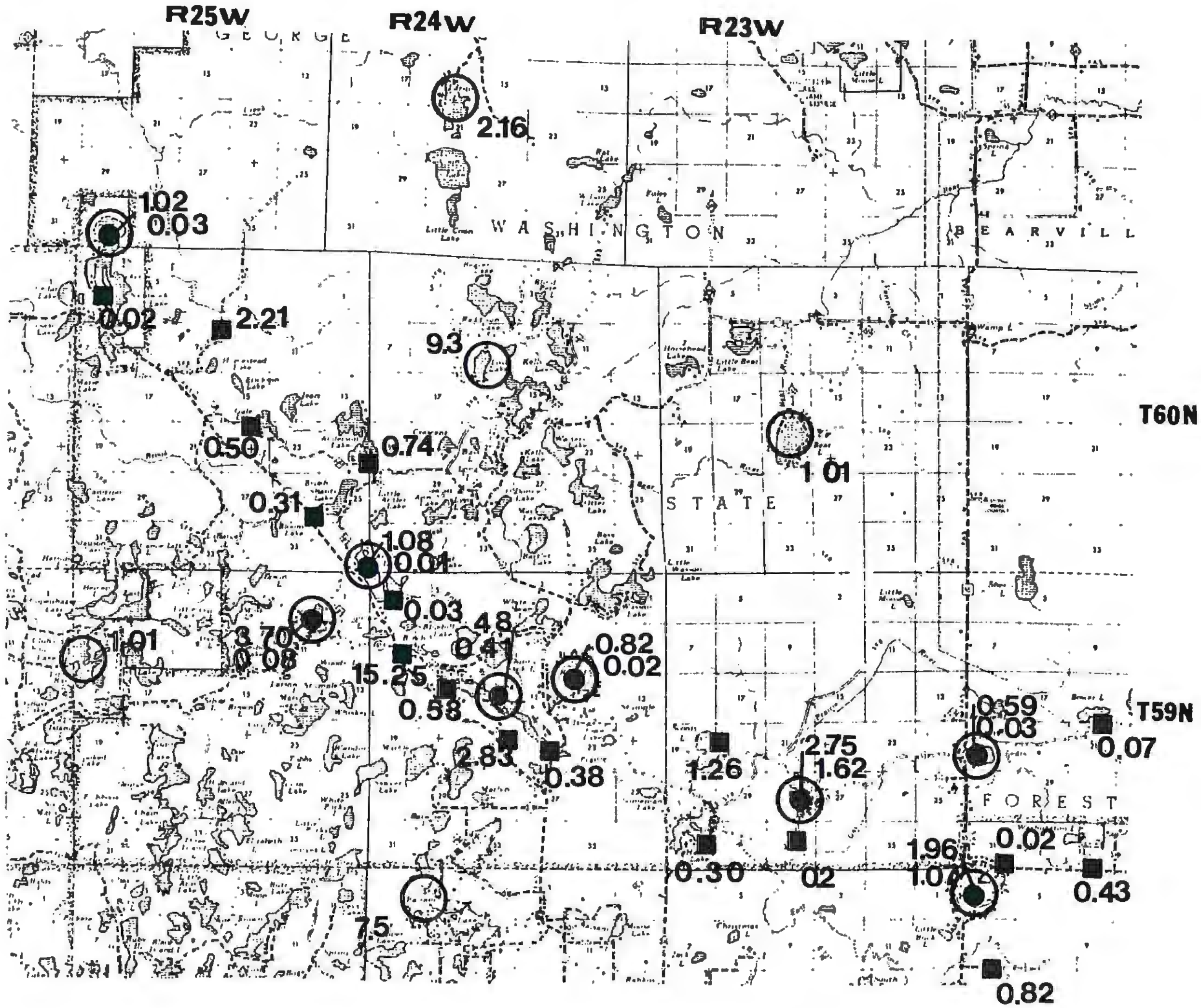
Cobalt Concentrations for Lake Sediment Data Only .
(in ppm)



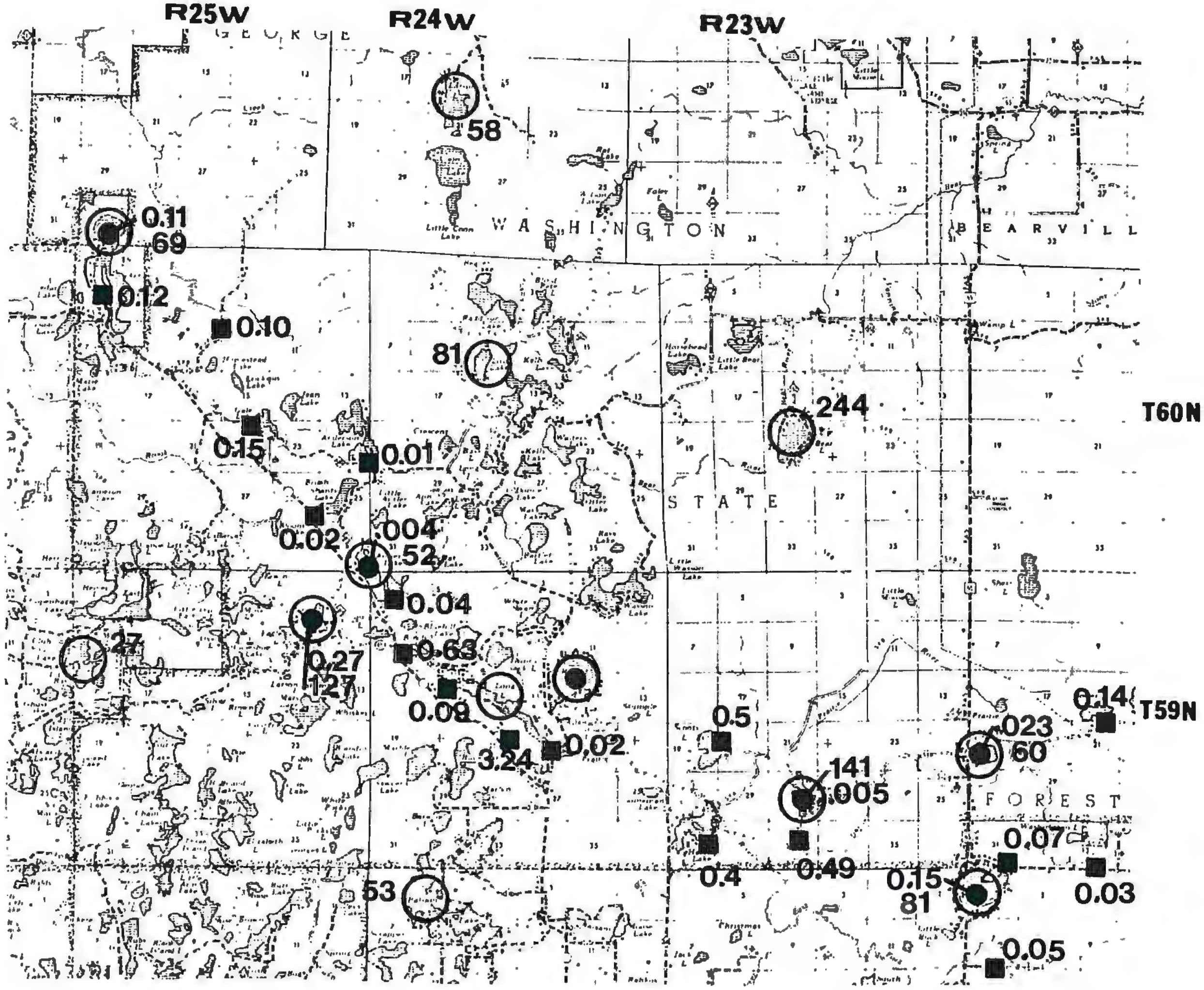
Copper concentrations (in ppm) FOR LAKE SEDIMENT ONLY.



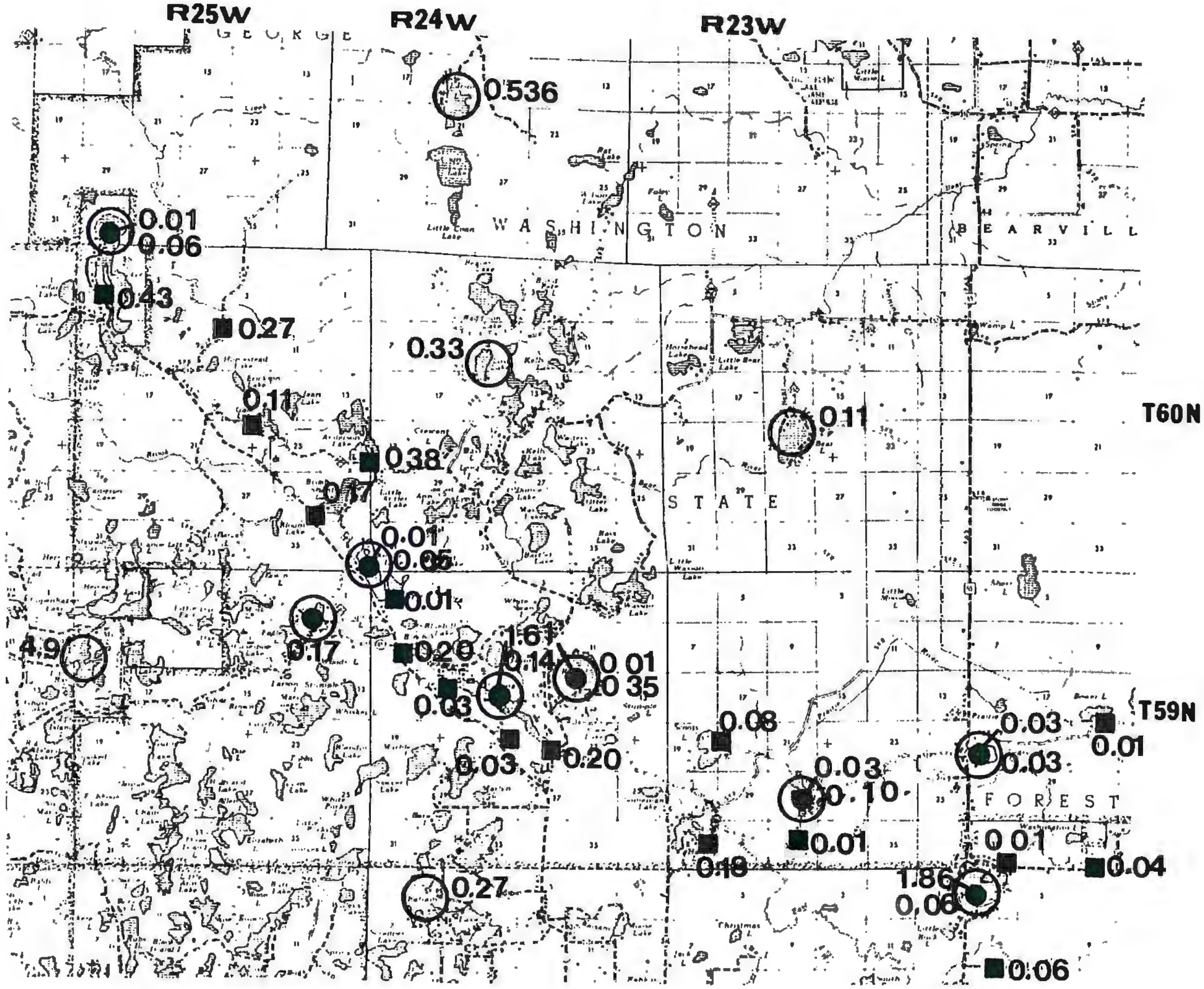
Nickel concentrations (in ppm)



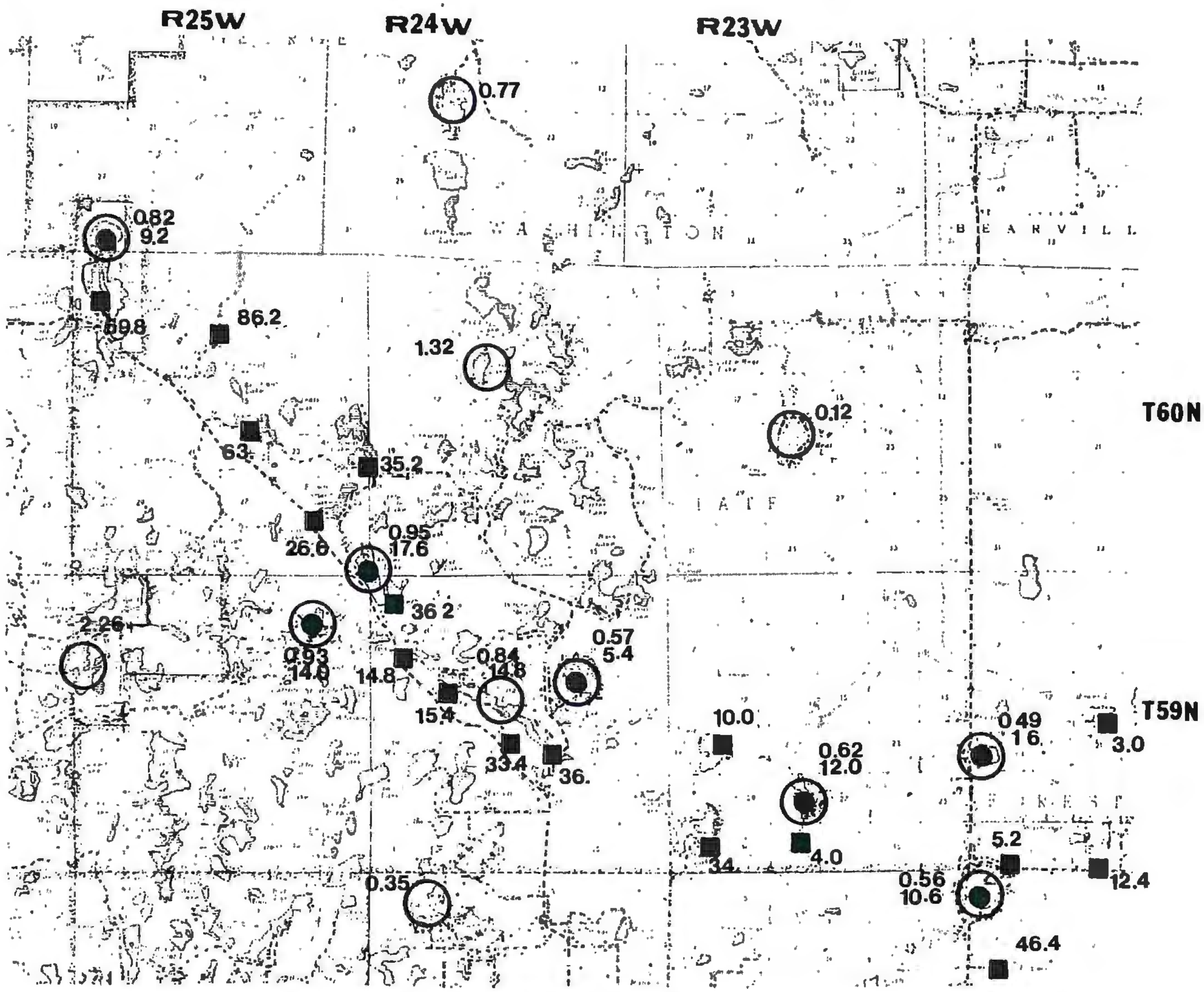
Iron concentrations (in weight %)



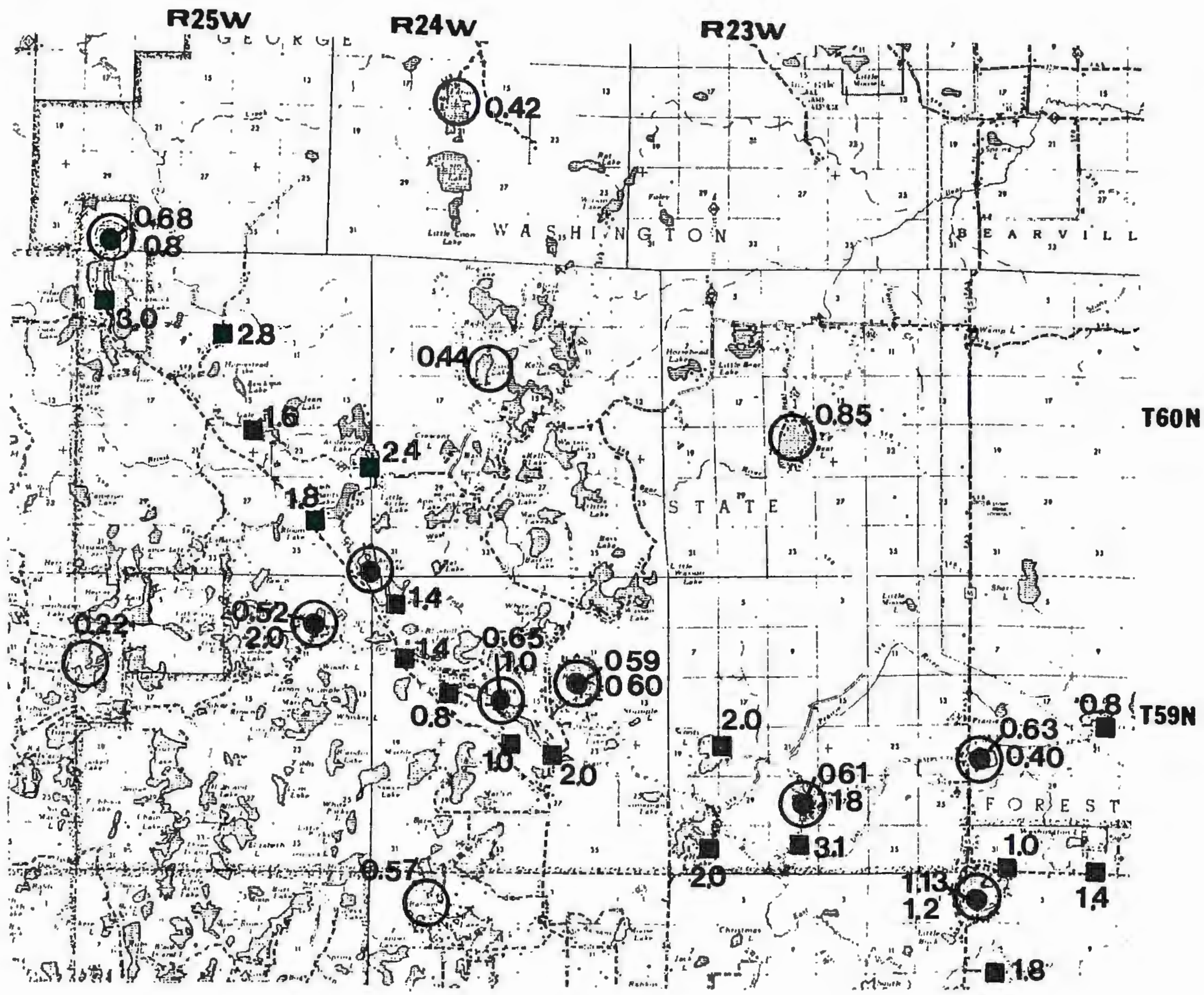
Zinc concentrations (in ppm)



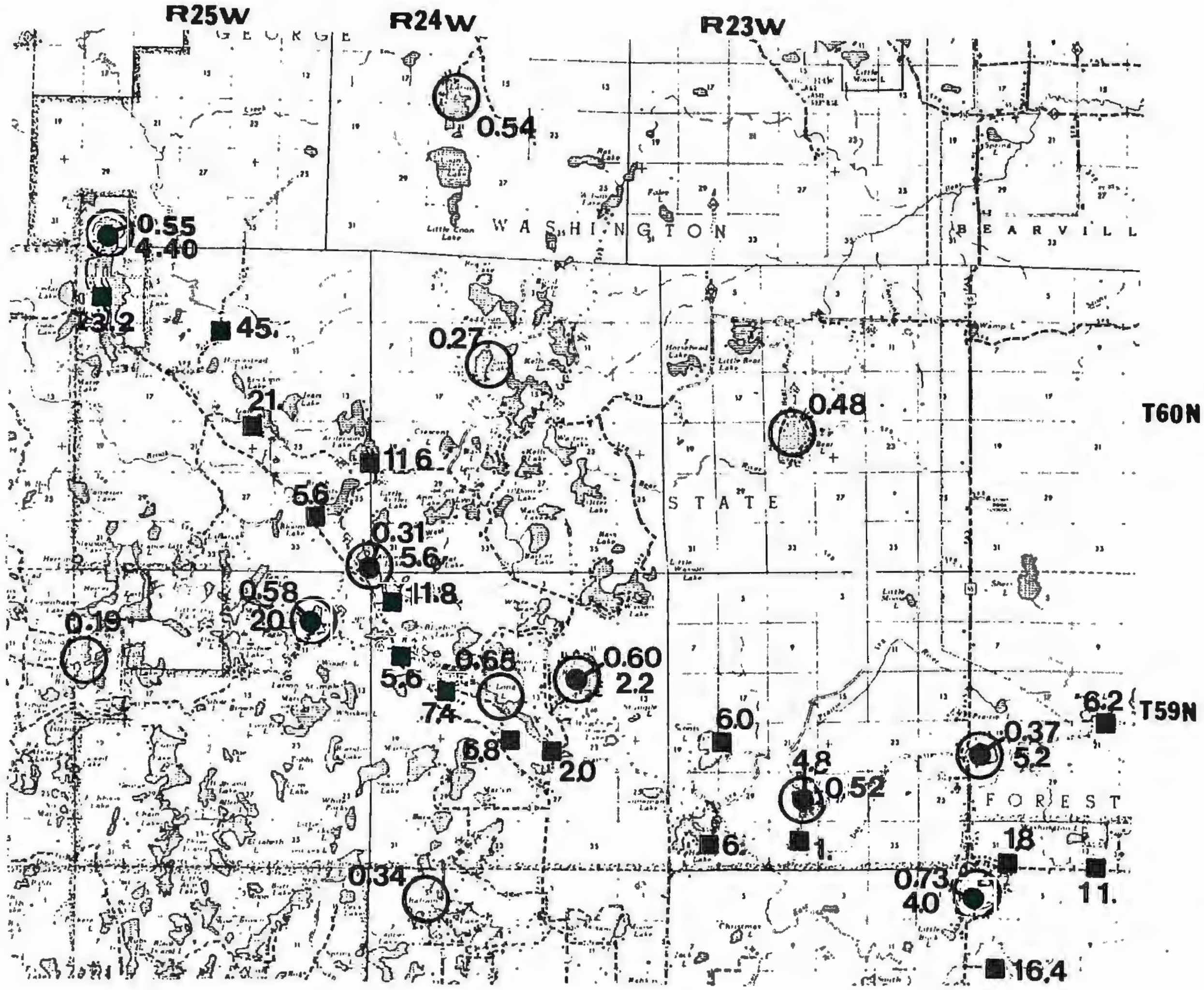
Manganese concentrations (in weight %)



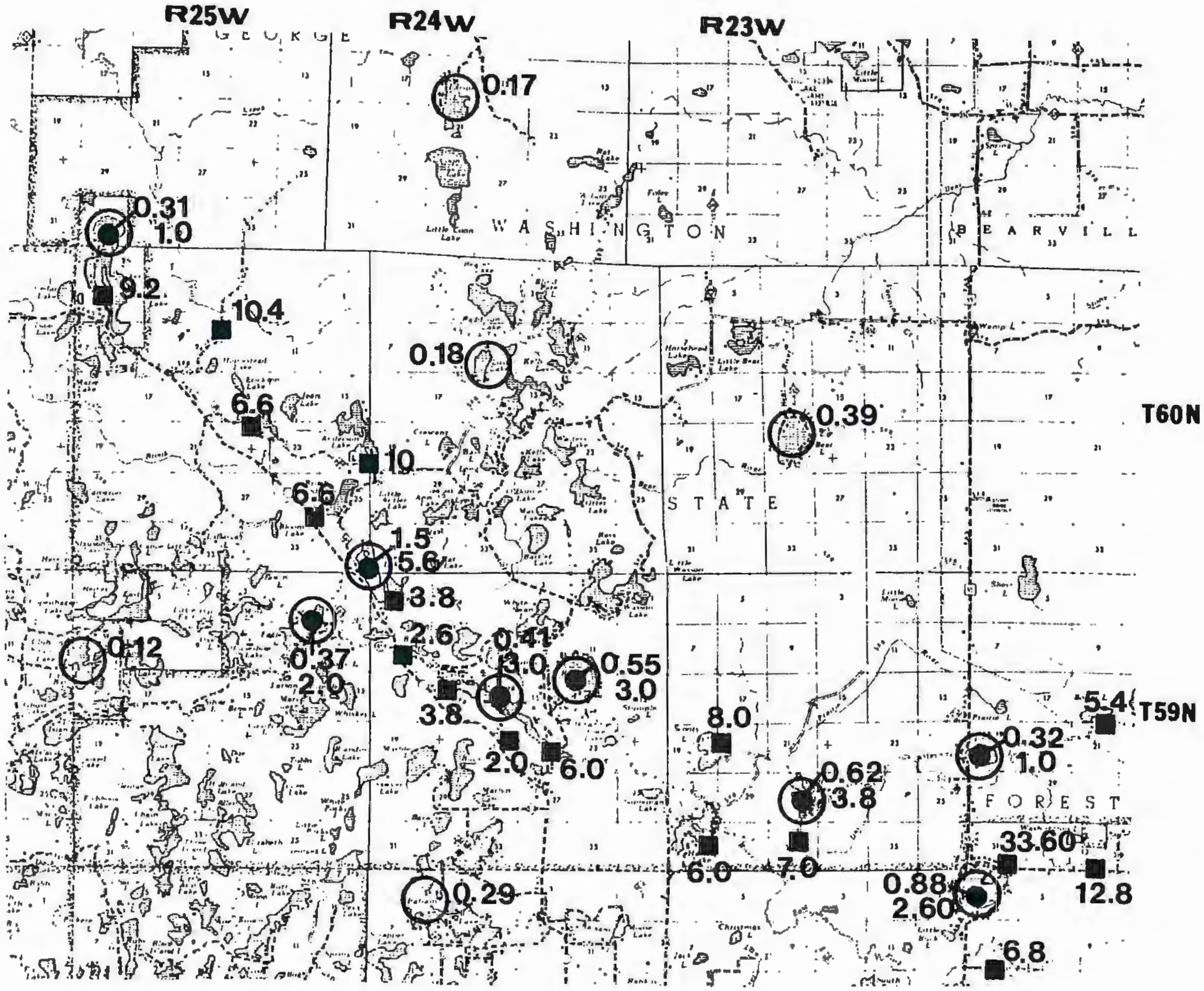
Calcium concentrations (in weight %)



Potassium concentrations (in weight %)



Magnesium concentrations (in weight %)



Sodium concentrations (in weight %)